A FIRST REFERENCE SPATIAL REMOTE SENSING AND AGRONOMIC KNOWLEDGE BASE FOR PRECISION AGRICULTURE AND RELATED APPLICATIONS

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Abstract

The present article constitutes a review of the innovative approaches and results obtained in the ADAM project, dedicated to the „Assimilation of spatial Data into Agronomic Models", a scientific collaboration between France and Romania. The results mainly refer to the following aspects: (i) constitution of the first reference spatial remote sensing and agronomic knowledge base for scientific investigation; (ii) production of a SPOT XS/XI time series of high quality satellite images; (iii) validation of a method for monitoring soil surface moisture throughout crop phenological cycles, using SAR (ERS-2 and RADARSAT-1) images and the "water cloud" model; (iv) definition of the revisit frequency of satellites for the field-scale agriculture; (v) development of an efficient strategy of variational assimilation of spatial data into agronomic models, by exploiting the high spatial coherence that characterizes the crops during their development; (vi) calculation of the adjoint model of the complex canopy functioning model STICS by automatic differentiation; (vii) improvement of the canopy radiative transfer modeling by accounting for the leaf clumping, and elaboration of the CLAMP model.

Furthermore, this article presents other studies, led to valorize the "ADAM knowledge" after this project had finished. These are primarily related to the development of pattern analysis algorithms (i.e., advanced data mining for efficient extraction of information on spatio-temporal phenomena from Satellite Image Time Series / SITS, and data fusion for multi-resolution decomposition, by using the morphological pyramid technique), which the high quality of the ADAM knowledge base made possible.

Being free for scientific studies, with easy access through the Kalideos Portal, the ADAM knowledge base still has the potential to produce other notable findings (http://kalideos.cnes.fr/spip.php?article68).

Key words: field-scale agriculture, spatial remote sensing, satellite revisit frequency, leaf clumping, data assimilation, STICS, CLAMP, ADAM project, SITS

1. Introduction

In the 1990s, precision agriculture was asking for new solutions, because its requirement of timely, updated, localized information was not being met only based on radiometric data. To find appropriate solutions, the European Space Agency commissioned a study, which revealed the following general needs of the agricultural market (ALS-IT *et al.,* 2000): (i) farmers were expecting weekly information (in the form of 5 to 10 spatial[1] products about crop and soil conditions) during the entire growing season, provided in less than 72 hours after acquisition, on a yearly subscription basis, at an affordable price (in EUR/ha or $/acre) depending on the crop and country; (ii) commodities traders, governments and trade insurance were expecting to directly buy spatial products on large areas, without distribution networks.

At the same time, the French Space Agency (CNES), within the framework of its activities concentrated on the development of technologies for priority applications, was interested in the design of spatial missions dedicated to the monitoring of the agricultural lands, according to the modes of surveillance and warning used operationally in meteorology and oceanography.

In this vision, the assimilation of spatial data into agronomic models was a promising approach (Guérif and Duke, 2000; Baret *et al.,* 2000).

Consequently, CNES initiated the scientific project "Assimilation of Spatial Data into Agronomic Models" (ADAM) in order to investigate how to provide such information by satellite remote sensing (http://kalideos.cnes.fr/spip.php?article68).

From 2000 to 2004, Romania collaborated within ADAM. The other organizations involved, except CNES, were the French National Institute for Agricultural Research (INRA) of Avignon, the National Research and Development Institute in Soil Science, Agro-Chemistry and Environment (ICPA Bucharest), the National Research and Development Institute in Agriculture (ICDA Fundulea) and the Romanian Space Agency (ROSA). The main objective was to analyze the use of the spatial data of high temporal and high spatial resolution, for a detailed characterization of the vegetation canopies functioning, aiming specifically at improving agricultural land and crop management.

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[1] In this paper, „spatial" has two senses: one is related to Outer Space (e.g., spatial data and spatial products), while the second is not related to it (e.g., soil spatial sampling).

2. Objectives, Novel Approaches and Methods

An economic and environment friendly agricultural land management involves, among other actions, optimal control of exogenous inputs (e.g., fertilizers, water of irrigation, pesticides, and herbicides) and, therefore, requires a dynamic evaluation of the crop status, as well as timely identification of the areas affected by mineral deficiencies, water stress, disease, weeds, pest attack and lodging (in cereals). This monitoring is essential in the context of precision agriculture, the peculiarity of which is exactly the need for updated, localized and detailed information on crop and soil condition, in order to optimize the amount of inputs for every relatively homogeneous area of a field (Moran *et al.,* 1997; Stafford, 2000; Baret *et al*., 2000).

Turning to the capabilities of the space technology around the year 2000, time series of high spatial and high temporal resolution data were not available, in order to ensure agricultural land monitoring in an operational way.

At the same time, several results of research demonstrated that agronomic information at the field scale can be produced by spatial remote sensing. For example, Guérif and Duke (2000) and Baret *et al.* (2000) showed that the agricultural crop condition and the phenological stage could be estimated, if the knowledge on the physical and physiological processes had been taken into account in an explicit way. To this end, the joint use of an agrophysiological model and a sequence of radiative transfer (RT) models, accompanied by an explicit exploitation of the temporal dimension of the satellite data, had to better control the simulation of crop development, leading to more accurate simulation of the canopy functioning.

These assumptions were verified in the ADAM project by the concurrent use of three SPOT satellites operational during the project, in order to ensure the high temporal resolution (Baret *et al.,* 2001). The goal was to verify if the information necessary for the optimal management of relatively homogeneous areas within fields could be produced by spatial remote sensing, with the accuracy and timeliness demanded by the precision agriculture techniques and the cereal markets. The data assimilation approach, belonging to an advanced mathematical method, was innovative for agriculture and aimed at providing this information at the field or sub-field scale. In fact, the technique of assimilation of spatial data allows exploiting their temporal dimension in a satisfactory way, which is necessary to characterizing the intrinsically dynamic functioning of the agroecosystems. Besides, the coupling of the models allows explicit information exchanges. Thus, the crop functioning (agrophysiological) model can provide a dynamic description of some canopy state variables toward the RT model and, thus, can pass information onto its structure.

2.1. Simultaneous Assimilation of Spatial Data over Contiguous Pixels

In this respect, Lauvernet *et al.* (2002) and Lauvernet (2005) developed a strategy to assimilate spatial data in the canopy functioning models, by adapting a variational method of optimal control that used the calculation of the adjoint model (Le Dimet and Talagrand, 1986), the performance of which had been proved in meteorology and oceanography. The adjoint was calculated for two strongly contrasted levels of complexity of the canopy functioning description: (i) a simple model of the leaf area index evolution (BONSAÏ, developed in ADAM); (ii) a generic, complex agrophysiological model (STICS by Brisson *et al.*, 2003).

Compared to the quoted method of Le Dimet and Talagrand, Lauvernet (2005) proposed a simultaneous assimilation of satellite data over contiguous pixels (e.g., pixels covered by fields organized around the same cropping systems, or cultivars having the same phenology), an improvement that was possible because of the high spatial and temporal coherence of the agricultural land. In this way, the dimension of the control space decreased, as compared to a „pixel-by-pixel" assimilation strategy. This is a significant improvement, because mathematically the latter is an ill-posed problem, often not enough spatial data being available.

2.2 Improvement of the Canopy Radiative Transfer (RT) Modeling by Accounting for the Leaf Clumping

To add more performance to the assimilation process, which depends on the quality of the models used, an important part of ADAM was dedicated to the improvement of the radiative transfer modeling in vegetation canopies. Around 2000s, the commonly used RT models were built in the form of uniformly distributed leaf layers. Nevertheless, in the case of the agricultural crops, this simplified representation was not realistic, mainly because of three reasons: (i) leaves are more or less clumped around the stems; (ii) crops are sown in rows; (iii) environment is discontinuous.

Given this inadequacy of modeling, the chosen approach consisted in building a model of the canopy architecture, which included an effective representation of the leaf clumping. For this purpose, Rochdi (2003) elaborated a generic formalism using 3D numerical models of canopies, which could represent the clumping effect continuously, starting from randomly located leaves to a fully clumped condition. The description of the clumping was fitted on measurements of the monodirectional and bidirectional gap fraction [2].

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[2] The *gap fraction* is defined as "the chance of not hitting a leaf when casting a ray through vegetation canopies". This parameter is often taken into account in the RT modeling.

2.3. Revisit Frequency of Satellites for Monitoring Crops at the Field Scale

A medium-term objective of CNES, mentioned in the introduction, was the development of space missions dedicated to the monitoring of the agricultural land at a local scale (field), making it possible to warn in case of water stress, mineral deficiencies, lodging, disease, weeds or pests.

The investigations carried out in ADAM specifically focused on the definition of the temporal resolution (i.e., satellite revisit frequency) of the observations that provide the necessary information for the management of relatively homogeneous areas of the fields, with reasonable accuracy and at affordable prices for the market (Vintila *et al*., 2005; Vintila and Baret, 2007). The approach consisted in the simulation of various frequencies of space observations, by using the depointing capability of SPOT series of satellites to increase the revisit frequency, and then assess the consequences of the temporal sampling on the estimation of the leaf area index (LAI). LAI was chosen because it is the most influential biophysical variable related to the crop functioning that can be estimated from optical data. The simulated scenarios of image acquisition took into account: (i) the uncertainties associated with the estimation of LAI from satellite optical data; (ii) the risk of cloudiness during satellite overpasses; (iii) a wide range of satellite revisit frequencies.

2.4. Estimation of the Surface Soil Moisture throughout Crop Cycles

Simultaneously with the investigations described above, which were all based on a high quality time series of optical data, acquired by the SPOT constellation, and intended chiefly to estimate LAI, a complementary study was conducted concerning the estimation of the surface soil moisture throughout the phenological cycle of the crops (Prévot *et al.,* 2003). This study exploited ERS-2 and RADARSAT-1 radar data, and used the "water cloud" model. The purpose was to validate the production of multitemporal maps of surface soil moisture, intended to be opportunely used as input in agrophysiological models.

2.5. Creation of the ADAM Knowledge Base: a Reference Spatial Remote Sensing and Agronomic Data and Knowledge Base

In order to support all these scientific investigations, ADAM required the creation of a vast database with spatial remote sensing and agronomic data and knowledge, accompanied by metadata about its content and structure. The novel ideas behind the development of the ADAM knowledge base were, on one hand, its free, easy access for research studies, and, on the other hand, due to the data representativeness and the existence of metadata, its effective use by any scientist interested in the development of other applications, not planned initially (Favard *et al.,* 2004). Figure 1 concisely shows the ADAM objectives, approaches, and expected results, as well as further developments (in pattern analysis studies), which continued to exploit its knowledge base, after this project had finished.

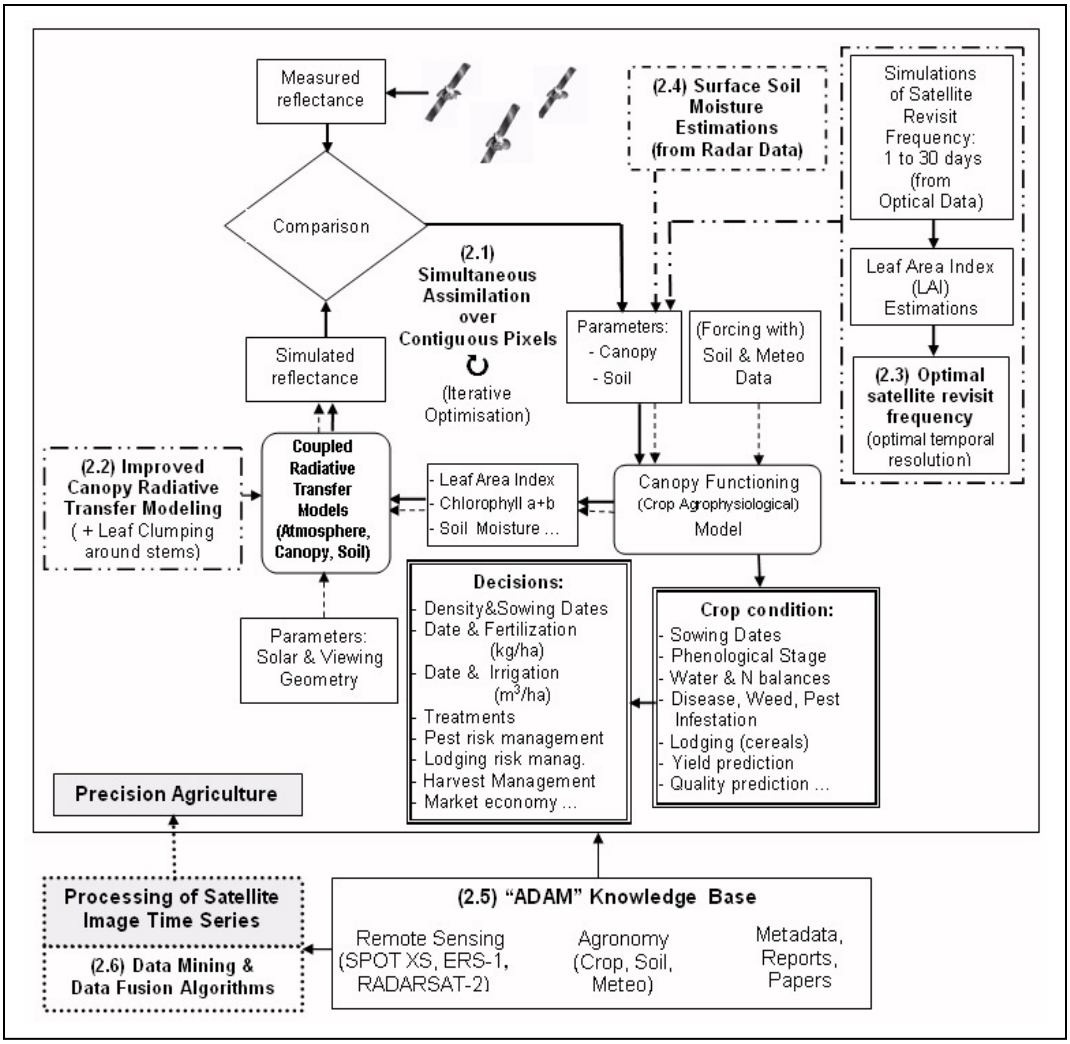

Figure 1 The ADAM Project: Objectives, Approaches and Expected Results in Precision Agriculture. Further Developments in Pattern Analysis.

2.6. Valorization of the ADAM Knowledge Base for Improving the Satellite Data Fusion and Mining for General Applications

Given the free, open status of the ADAM knowledge base, a first independent study gave a new solution for acquiring high temporal and high spatial resolution information for the monitoring of environmental processes at an affordable price.

To this end, Laporterie-Déjean *et al.* (2005) used the morphological pyramid technique and validated their approach by data fusion among high temporal & low spatial resolution (i.e., low price) images and low temporal & high spatial resolution (i.e., high cost) images, all with the same spectral bands.

During another research, Héas and Datcu (2005) published the results referring to an innovative concept and algorithm, based on a Bayesian network and a Dirichlet model, intended to solve the generic problem of the automatic recognition (identification) of different spatio-temporal phenomena in Satellite Image Time Series (SITS). The validation of this method was made on the SPOT TOA time series of ADAM.

In a more recent study, Julea *et al.* (2010) and Julea (2011) elaborated a novel method in order automatically to identify „grouped frequent sequential patterns" (defined as having "meaning for the end users") in satellite image time series. The method was validated both on radar and optical data, the latter represented by a selected set of images of the SPOT TOC time series of ADAM.

Although the studies enumerated in this paragraph addressed other issues compared with the objectives of ADAM, they succeeded in producing significant results in pattern analysis. These results become relevant also for precision agriculture, related to its requirement of timely information, and also because they are obtained in a noninvasive manner. Such efficient methods are becoming crucial when applied to the SITS to filter the useful information from irrelevant one, insofar as the amount of space data is ever growing.

3. Spatial Remote Sensing and Agronomic Data Collection

The experiment was organized in Romania, on a nearly flat agricultural site of about 20 x 20 km^2 (Fundulea-Ileana area), with the coordinates of the center at Lat=44°27'38.43" N and Lon=26°37'14.34"E. The ADAM site was chosen because of several advantages related to the project objectives:

- (i) Possibilities for SPOT data acquisition at high temporal resolution, the site being situated in direct viewing of two ground receiving stations (situated in Toulouse, France, and Kiruna, Sweden), meanwhile remaining sufficiently away from areas with strong demand for programming (to prevent a possible competition with commercial applications). It should be noted that, for the first time, this project ensured the framework to acquire a series of images with high repetitivity (quasi daily) with SPOT 4, 2 and 1 satellites (listed here in the order of the acquisition priority that was defined in the project);
- (ii) Local human and material resources for intensive ground measurements of high quality, performed in well controlled conditions by researchers of ICPA Bucharest and ICDA Fundulea;

- (iii) Large agricultural fields (15-40 ha), characterized by both intra-variability and inter-variability, making thus possible the calibration and validation of the models and innovative approaches.

Canarache (2002) gave a detailed characterization of the climate and soil coverage of the ADAM site. Also, this author together with Petcu *et al.* (2003) highlighted the properties and weather regimes of interest for the development of the agricultural crops in this area.

The spatial data acquisition and ground measurements were intensive during one reference agricultural year (October 2000 - July 2001) and lighter during the next years. In total, on more than 300 images acquired by the SPOT constellation, 57 multispectral optical images (XS/XI) were ordered on the ADAM site, among which 39 during the reference year. To correct these images of atmospheric effects, an automatic sunphotometer Cimel was installed in the site center, then calibrated and connected to the Aeronet network (http://aeronet.gsfc.nasa.gov, "Bucharest"). It provided the characterization of the atmosphere (i.e., sky irradiance, water vapor, aerosol optical depth, and particle size distribution) at the time of the satellite overpasses.

In addition, to meet the objective of the surface soil moisture estimation, several SAR images were acquired during the reference year. Therefore, four ERS-2 [3] and six RADARSAT-1[4] were processed.

The meteorological data, which were needed by the radiative transfer and agrophysiological models, were collected by an automatic Campbell weather station. The types of data used throughout the project were: air temperature and relative humidity, wind speed and direction, rainfall, potential evapotranspiration, soil temperature profile up to 100 cm depth, global radiation and photosynthetical active radiation (PAR) (total, direct and diffuse PAR).

The Romanian team carried out the field work, following particular strategies as concerns the high spatial and temporal sampling during the cultural year. The investigations focused on winter wheat (*Triticum æstivum* L.), due to its overall importance and existence of relevant expertise in robust simulation tools.

The ground observations and measurements concerned inputs needed by the calibration and validation of the models, namely:

- (i) soil properties: depth, albedo of dry bare soil, organic matter, chemical

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[3] C-band, incidence angle 23°, and V V polarization

[4] C-band, HH polarization, and low-incidence angle mode; this operation mode was specially selected to minimize the effects of vegetation and soil roughness

characteristics (N_{total}, N-NH_4, N-NO_3, $P_{available}$, $K_{available}$, cation exchange capacity, pH, and $CaCO_3$), and physical characteristics (texture, bulk density, suction curve, moisture at the field capacity, hygroscopic coefficient, profile soil moisture, surface soil moisture, roughness, resistance to penetration, infiltrability at the lower limits of the horizons, and temperature);

- (ii) wheat crops properties and observations: phenological stage, plant height, leaf area index, chlorophyll a and b, total above-ground biomass, biomass partitioning (green leaves, senescent leaves, stems and ears), total nitrogen content in leaves, rooting system depth, root structure, weeds and pests control, yield components, and grain quality (protein);
- (iii) other characteristics of the fields: depth of the groundwater table, row orientation, row spacing, other elements of the cropping systems.

In each cultural year of the project, accurately geo-referenced "Elementary Sampling Units" (ESUs) were defined on the wheat fields, where the measurements were being performed.

The ESUs were defined as follows :

- (i) reprezentativity: the ESUs had to be representative of the field intra- and inter-variability of the site, as regard factors of significant variation (i.e., wheat cultivar, sowing date, soil type, previous crop, fertilization, irrigation, and micro-topography);
- (ii) size: an ESU was a little larger than a SPOT XS/XI pixel (i.e., a disc of about 30 m in diameter), to account for the co-registration errors, which are inherent to the satellite image time series;
- (iii) spatio-temporal identification: the ESUs had to be recognizable in the SPOT XS/XI time series; for this, groups of 5 x 5 contiguous, quasi-homogenous SPOT XS/XI pixels around the ESUs were also taken into consideration, the median of their reflectance values being later used in processing;
- (iv) field position: the ESUs had to be established sufficiently within the fields (such as groups of 5 x 5 pixels were also fully included), however, keeping a suitable distance from borders, for efficient accessibility.

The Elementary Sampling Units were divided into two groups:

- (i) ESUs for the calibration of the radiative transfer model and crop functioning models; on these units, the measurements were the most complete and frequent (on a weekly basis);
- (ii) Units for the validation of models and results of the spatial data assimilation; on these units, the measurements were less complete and less frequent (about every month). During the reference year, 42 ESUs were established, 10 for calibration and 32 for validation.

Figure 2 illustrates the spatial distribution of several ESUs and the quasi-homogenous area (5x5 pixels) considered around them.

Figure 2 Example of Spatial Distribution of Elementary Sampling Units (ESUs) and their Neighboring Areas of Representativeness

The number of ESUs was significantly reduced during the next years. Further details of this experiment are described by Baret *et al.* (2001), Vintila and Baret (2007) and in the documentation available in the ADAM knowledge base.

4. Results and Discussions

The ADAM project introduced the concept of "reference remote sensing database" (Favard et al., 2004), which is now extended far beyond the objectives related to precision agriculture, leading to the Kalideos Portal developed by CNES for research (http://kalideos.cnes.fr/spip.php?article68).

With regard to the ADAM database, it was deliberately oversized from the point of view of time sampling, to allow the elaboration of an efficient data assimilation strategy, including in terms of the number of satellite images (Baret *et al.,* 2001).

For the creation of the remote sensing database, firstly a SPOT 4 image was chosen so that several requirements were met to become "the geometric reference": high radiometric quality, near-nadir acquisition, almost no clouds all over the scene. This image was geometrically corrected and orthorectified by the Romanian team in the Gauss-Krüger projection on Krasovsky 1940 ellipsoid and S-42 datum, according to the usual method. The phases accomplished were: (i) use of proper satellite parameter model (which includes its attitude and orbital parameters) and registration (based on a dense network of control points, which had been measured on the ground with Differential GPS); (ii) use of a local Digital Terrain Model to correct the relief effects; (iii) bilinear resampling of digital values to the new grid; it is worth mentioning that the cubic convolution resampling would have been more appropriate for the purposes of ADAM, but was not available in the available software.

Secondly, based on this geometric reference, the other 56 SPOT images were co-registred by automatic correlation, which was performed with the Tarifa preprocessing chain developed by the PS/TIS team of CNES. This stage of the geometric correction took several months, three successive versions of increasing quality being produced. The best overall accuracy of the image co-registration was of the order of 10 m throughout the scene (60 x 60 km^2) centered on the ADAM site, which corresponds to 0.5 SPOT XS/XI pixel.

Concerning the radiometric corrections of SPOT images, they were made at CNES starting from refined calibration coefficients, which took into consideration the temporal evolution of the HRV/HVIR sensors. Next, the information from the Aeronet Server, estimated from the local data collected by the Cimel photometer, was used to correct the atmospheric effects

Finally, two time series of high quality images were produced: (i) the time series of the reflectance values at the top of atmosphere level, called SPOT TOA; (ii) the time series of the reflectance values at the top of canopy level, called SPOT TOC; the latter was the most used for the detailed characterization of the wheat crop development during ADAM. It should also be noted that, *until recently, the 39 SPOT XS/XI images, which were ordered over the same region in the reference year, represented the most concentrated (temporal densest) satellite image time series at high temporal and high spatial resolution.* It made possible, by its temporal oversizing and high quality, the planned research investigations for the benefit of precision agriculture (Baret *et al.,* 2001; Oro *et al.*, 2003), as well as several studies on pattern analysis (Laporterie-Déjean *et al.*, 2005; Héas and Datcu, 2005; Julea *et al.*, 2010; Julea, 2011).

In order to assist at data localization and calibration of radar images, two trihedral corner reflectors were installed on the ADAM site at the beginning of the experiment (Radnea *et al.,* 2005). The radar images were first corrected geometrically using the parameters of the satellites, then orthorectified and finally resampled at 20 x 20 m^2, to ensure the spatial coherence with the SPOT XS/XI images. The numeric values associated with each of the pixels were then transformed into backscattering coefficients (σ°), according to the algorithms developed by the European Space Agency for ERS-2, and the Canadian Space Agency for RADARSAT-1. *The main result obtained in ADAM from exploiting the radar images was the demonstration that the semi-empirical model "water cloud" satisfactorily simulates the radar signal backscattered by wheat canopy over its cultural cycle, and thus it may be possible to monitor the surface soil moisture with reasonable accuracy throughout the entire cultural year, including when the soil is covered by crops (Prévot et al., 2003).* Figure 3 shows the relatively good performances of the surface soil moisture (ssm) estimation over the ESU calibration units, particularly in the case of ERS-2 satellite observations.

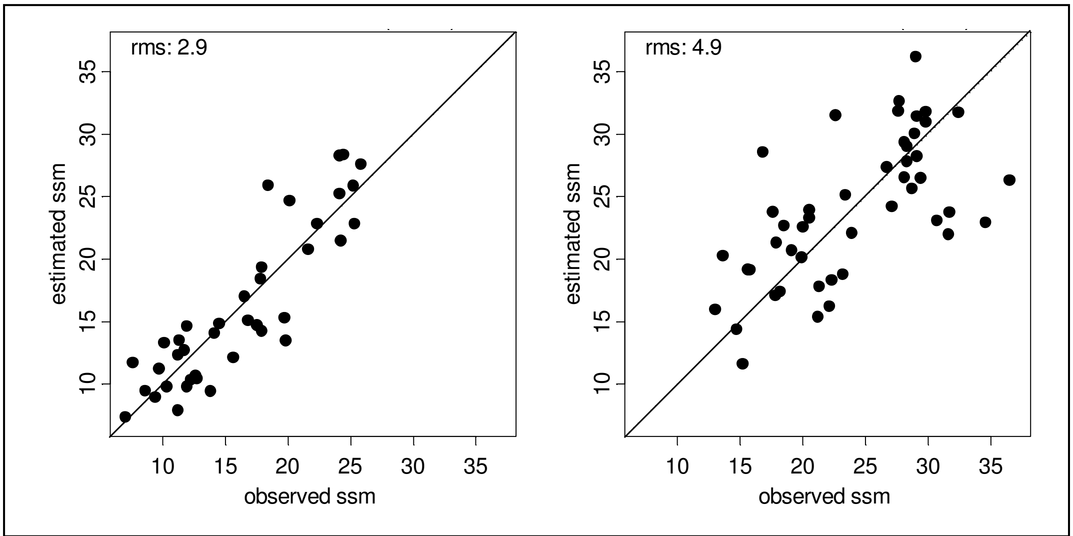

Figure 3 Comparison between ground measurements of the soil surface moisture (ssm, % g/g) with the estimations from the inversion of the “water cloud” model (ERS-2: left side; RADARSAT-1: right side)

Another output of the project was the definition of the temporal resolution of satellite data for field-scale agriculture. This result was obtained by monitoring the

LAI over the wheat fields and analyzing the impact of the satellite revisit frequency on the estimation of LAI evolution (Vintila *et al.,* 2005; Vintila and Baret, 2007).

For this purpose, many image acquisition scenarios were simulated, which took into account the LAI variability, as well as the following pertinent assumptions (Figure 4): (i) three levels of uncertainty (modeled as additive gaussian noise) on LAI estimates from spatial observations: 10%, 20% and 25%; (ii) two levels of probability of the daily occurrence of clouds: 0.5 and 0.7;(iii) six revisit frequencies, covering the existing possibilities of sensors: 1, 2, 3, 7, 15, and 30 days.

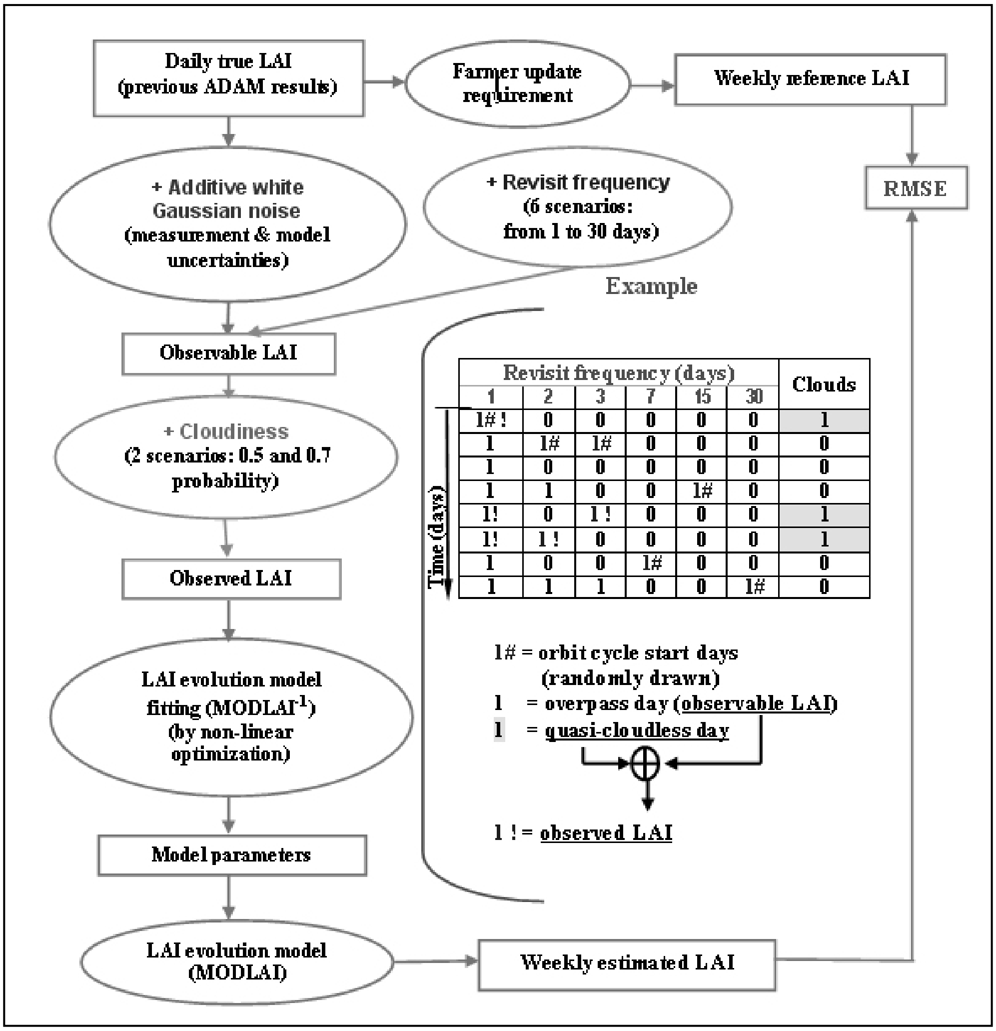

Figure 4 Algorithm for the definition of the temporal resolution of satellite observations for precision agriculture, based on the performance of LAI statistical estimation

The lack of temporal continuity of the estimated values was overcome by running the semi-empirical model MODLAI, proposed by Baret and Guyot (1986), which simulates the LAI evolution as a function of the accumulated daily mean air temperature, starting from sowing. On the ESU calibration units of the reference year, the coefficient of determination was R2 ≈ 0.96 and RMS Errors ≈ 0.28 between ground measured LAI and estimated LAI by linear multiple regression, using the SPOT TOC time series (Vintila and Baret, 2007). Also, MODLAI demonstrated good capacity to describe the LAI evolution on the ESU validation units. The results of more than 33,000 simulation scenarios, which are synthesized in Figure 5, showed that the LAI estimation errors were low and quite similar up to the satellite revisit frequency of 7 days, regardless of the uncertainty levels in LAI estimation and cloudiness probability. *The conclusion was that, in the near future, it will be possible to provide pertinent information on crop status to the farmers, at an affordable price and noninvasively. This will be done by combining weekly spatial data at 5-10 m spatial resolution (which is also compatible with the spatial accuracy of farm machinery), with limited knowledge on the canopy structure evolution (e.g., knowledge given by a simple LAI model) (Vintila and Baret, 2007).*

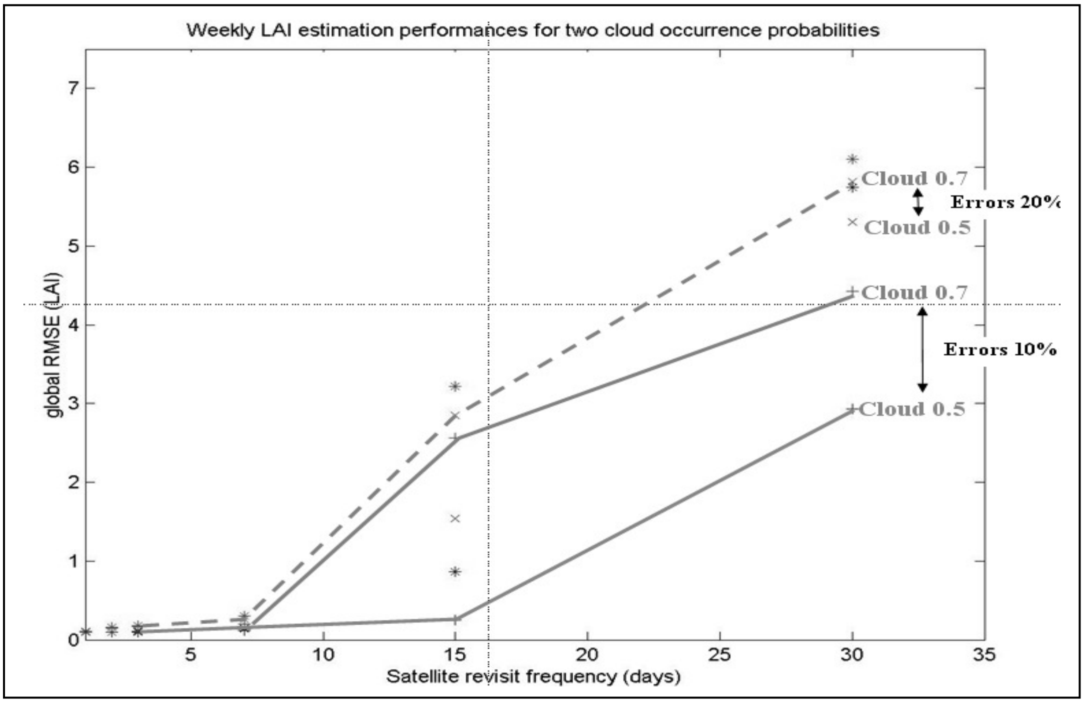

Figure 5 LAI estimation performance as function of revisit frequency

Turning now to the spatial data assimilation objective of ADAM, illustrated in the very center of Figure 1, Lauvernet (2005) successively coupled a simple, then a complex crop functioning model, to a radiative transfer (RT) model. The selected RT model was PROSAIL, that, in fact, is the combination of two widely used models during last two decades: (i) PROSPECT, developed by Jacquemoud and Baret (1990) to calculate leaf-level reflectance and transmittance spectra; (ii) SAIL, elaborated by Verhoef (1984), to simulate the bi-directional spectral reflectances, based on a physical description of the canopy radiative transfer.

(i) The first crop functioning model used was BONSAÏ that only simulates the LAI evolution. BONSAÏ is, in fact, an improved version of MODLAI, by the introduction of the sowing date as an additional parameter. Lauvernet calculated BONSAÏ adjoint model with Tapenade automatic differentiation engine (http://www-tapenade.inria.fr:8080/), then adapted the variational data assimilation strategy of Le Dimet and Talagrand (1986), first on a "pixel-by-pixel" basis. Among other strictly mathematical relevant results, this spatial data assimilation approach confirmed the previous finding of Vintila and Baret (2007) related to the temporal resolution of satellite observations of 7 days. The next step was to take into account the intrinsic spatial coherence of the agricultural land. This fact was possible since some BONSAÏ parameters were similar for all the pixels of the same wheat cultivar (i.e., same phenological development, density and leaf properties) or the same field (because of the same cropping systems). In this respect, *an innovative strategy of simultaneous assimilation of spatial data over contiguous pixels was validated, which decreased the temporal resolution of satellite observations up to 15 days, while keeping the LAI estimation accuracy.*

(ii) Further, Lauvernet assessed the strategy of data assimilation on a "pixel-by-pixel" basis using the complex agrophysiological model STICS (Brisson *et al.*, 2003). STICS is composed of seven modules, of which three calculate the above-ground crop condition (i.e., LAI, biomass, and allocation to grains), while the other four simulate the soil water and nitrogen budgets, the root growth and transfers of water and nutrients between the soil and the above-ground biomass through the roots. At this point, *we must recognize as a breakthrough result the calculation of the adjoint of the STICS agrophysiological model (Lauvernet, 2005), by using the same automatic differentiator as above.* Through the adjoint of STICS, spatial sensitivity analyses of two model state variables, LAI and the biomass, were conducted on two wheat cultivars (Flamura and Dropia) and in the various conditions characterizing the ADAM site fields during the experiment (Baret *et al.,* 2001; Canarache, 2002). The goal was to rank the local importance of the cultivar parameters that drive the evolution of LAI and that of biomass, and subsequently to build an improved simultaneous assimilation strategy over contiguous pixels covered by crops having the same phenological development (Lauvernet, 2005).

Contrary to BONSAÏ, we have to mention that the strategy of simultaneous assimilation of spatial data over contiguous pixels was not validated on STICS during ADAM, because of lack of time. On the other hand, the results obtained in the development of strategies for spatial data assimilation for precision agriculture were widely recognized (e.g., Guérif *et al.,* 2006) and used in other studies.

A last result to report obtained in ADAM concerns the improvement of the radiative transfer modeling by accounting for the leaf clumping at the canopy level.

Rochdi (2003) elaborated the CLAMP model (Clumped Architecture Model of Plant) to generate three-dimensional digital models for a wide range of canopy architecture, among which wheat and corn. Rochdi considered six structural variables as inputs: leaf area index, average leaf inclination angle, relative leaf size (S*), plant relative density (d*), relative leaf-stem distance and leaf shape. The variation of the leaf clumping was modulated by the relative leaf-stem distance, ensuring a gradual transition from the turbid medium, commonly modeled, to highly clumped canopies.

Then, Rochdi and Baret (2004) examined the sensitivity of the gap fraction as a function of the view zenith angle and input variables in CLAMP. Finally, a *parameterization of the clumping parameter (λ) of the canopy, characterizing the mutual dependence between leaf layers, was proposed, as a function of the view zenith angle (θ) and the relative leaf-stem distance (χ):*

$$\lambda(\theta) = a(\chi, S^*, d^*) + b(\chi, S^*, d^*)\exp[-c(\chi, S^*, d^*)\tan(\theta)] \qquad (1)$$

where a, b and c depend on χ, S and d*.*

This parameterization was applied to estimate several biophysical variables, such as the leaf area index and the average leaf inclination angle, by using hemispherical photographs taken on different vegetation canopies with fisheye lenses.

The results showed that, by this development in the modeling of the canopy radiative transfer, the LAI estimation was improved in the case of high LAI values and clumped canopies.

In addition to the research studies for precision agriculture, the ADAM knowledge base was used in pattern analysis research (data fusion and data mining).

The first results were obtained by Laporterie *et al.* (2005) in a study dedicated to the « Multi–resolution temporal fusion of high and low resolution image series using the morphological pyramid technique ». This study tried to address the need of frequent image acquisitions for the survey of vegetation condition regardless of scale. Even now, Earth monitoring relies on wide field-of-view sensors, such as MODIS on TERRA satellites, MERIS on ENVISAT, and VEGETATION on SPOT, with spatial resolutions between 300 and 1200 m that make impossible the discrimination of agricultural fields and the assessment of crop status.

The approach adopted by Laporterie *et al.* was data fusion using the morphological pyramid technique, in order to build virtual images with physical significance. This goal was achieved by selecting compatible spectral data: on one hand, high spatial (20 m) & low temporal resolution SPOT 4 HVIR data (19 preprocessed images of the ADAM project), and, on the other hand, high temporal & low spatial (1000 m) resolution SPOT 4 VEGETATION simulated images. *This study succeeded in a spatial resolution ratio of the fused data of 1:50, for the first time, and gave an affordable solution to meet the need of frequent image acquisitions for detailed surveys (at high spatial resolution) of the vegetation condition.*

In another study, devoted to specific techniques for „mining" in Satellite Image Time Series (SITS), Julea *et al.* (2010) and Julea (2011) developed a method to simultaneously extract spatial and temporal information that can further assist photointerpretation. *The proposed method recognizes and extracts so called "grouped frequent sequential patterns", made up of sets of connected (contiguous) pixels sharing a same temporal evolution. This method, which is unsupervised and run at the pixel level, was validated both on radar and optical data, demonstrating, according to the authors, the quasi-genericness of the approach*. *The validation on optical data was performed by using 20 images of the SPOT TOC time series of ADAM, different pixels of the agricultural fields being automatically recognized with more or less accuracy, depending on their „purity"*[5].

In a third independent study related to ADAM, Héas and Datcu (2005) also approached the subject of innovative data mining techniques in SITS. Their paper *"Modeling Trajectory of Dynamic Clusters in Image Time Series for spatiotemporal Reasoning" (Héas and Datcu, 2005) received the "2005 Best Paper Award", granted by IEEE. This paper presents a novel algorithm to solve the generic problem of automatic recognition of spatio-temporal phenomena (e.g., crop development, harvesting, or ploughing campaign), algorithm that was validated on the SPOT TOA time series of ADAM.*

Being free for scientific studies, with easy access through the Kalideos Portal, the ADAM knowledge base still has the potential to produce other notable findings.

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[5] In the context of this paper, a "pure" pixel on the ground is covered by one crop, or even by one cultivar.

5. Conclusions

The ADAM Project was a successful scientific collaboration among several multidisciplinary teams from France and Romania, initiated at the end of 2000 by the French Space Agency (CNES) to investigate how to provide timely, updated, localized and reasonably accurate agronomic information at the field scale, at an affordable price, information produced in a noninvasive manner by using satellite remote sensing. ADAM constituted one of the first stages of the research initiatives in Europe resulting in the new space missions Pléiades, SENTINEL-2 and VENµS that meet the requirement for detailed surveys of the vegetation condition, all having high spatial and temporal resolutions:

- (i) Pléiades is a system of two small satellites developed by CNES and represents the optic component of ORFEO Program, the European observation system with metric resolution. The first satellite was successfully launched on 17 Dec 2011. The second satellite is planned for launch in 2013. Pléiades main technical characteristics are: (1) spatial resolution at nadir of 0.7m in panchromatic and 2.8m in multispectral (blue, green, red and near infrared bands); (2) field of view of 20km; (3) daily acquisition (http://smsc.cnes.fr/PLEIADES/index.htm);

- (ii) SENTINEL-2, which is also made of a pair of two identical satellites, is being developed by the European Space Agency to ensure the continuity of SPOT and LANDSAT-type data. In addition, SENTINEL-2 will “observe” the Earth with better technical characteristics: 13 spectral bands, spatial resolutions between 10 and 60 m, and 2 to 3 days revisit frequency at mid-latitudes. The launch of Sentinel 2A is planned for the second part of 2013, while Sentinel 2B will be launched at the beginning of 2015 (http://www.esa.int/esaLP/SEMM4T4KXMF_LPgmes_0.html);

- (iii) VENµS (Vegetation and Environment monitoring on a New Micro-Satellite) is being developed for scientific investigation by the Center for the Study of the Biosphere from Space (CESBIO) of Toulouse, CNES and the Ben Gurion University of the Negev (Israel). The focus of this mission will be on the vegetation affected by environmental factors (e.g., human activity). This will be monitored by a super-spectral camera with 12 spectral bands, 5.3 m spatial resolution at nadir, and 2 days revisit frequency. It is expected the satellite VENµS will be operational in 2014 (http://smsc.cnes.fr/VENUS/index.htm).

As regards the results of modeling obtained in ADAM, the degree of their generality could be enlarged by using the new spatial data and more documented assumptions, as well as by simulating other crops (including those having shorter phenological cycles, such as maize and sunflower).

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