

Agrometeorological study of semi-arid areas : an experiment for analysing the potential of FORMOSAT-2 time series of images in the Marrakech plain

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ABSTRACT

Earth Observing Systems designed to provide both high spatial resolution (10 m) and frequent time of revisit (a few days) offer strong opportunities for the management of terrestrial water and agricultural resources. The FORMOSAT-2 Taiwanese satellite is the first and only system with the ability to provide daily images over a particular area at a high spatial resolution and with the same viewing parameters. As part of the SudMed project, one of the first time series of FORMOSAT-2 images is presently being acquired every 4 days over the semi-arid Al Haouz/Tensift plain. Along with these acquisitions, an experimental data set has been collected during the 2005-2006 agricultural season. This communication aims at presenting this experiment as well as a first analysis of the potential of FORMOSAT-2 time series for agrometeorological study of semi-arid areas.

1 INTRODUCTION

Irrigated agriculture makes a major contribution to food security, producing nearly 40% of food and agricultural commodities on 17% of cultivated lands (FAO 2002). However, serious water shortages occur in arid and semi-arid areas as existing resources reach full exploitation. The design of tools for providing with land-use/land-cover as well as regional estimates of water balance and crop yield is necessary to ensure a sustainable development of these areas. This is one of the objectives of the SudMed project, which is carried out by CESBIO (Toulouse, France) and University Cadi Ayyad (Marrakech, Morocco). The project focussed on the Tensift/Marrakech basin as a pilot region. This region embodies a number of characteristics which make it a valuable laboratory for addressing a large number of scientific issues in arid and semi-arid regions (Chehbouni et al. 2005).

Effective management and monitoring of environmental resources require spatial data in order to incorporate the land-use features as well as hydrologic and vegetation parameters. Remote sensing may be the only feasible means of providing such information with a consistent space and time basis. Data acquired in the solar spectral domain has been the most intensively investigated in this context. Until

now, they have been collected by two types of systems: 1) high resolution sensors (ASTER, Landsat, SPOT-HRV); 2) large field-of-view sensors (MERIS, MODIS, SPOT-VEGETATION). The former acquires data at a fine spatial resolution (10m), but with revisit capacities of about 15 days which can be limiting for operational applications, especially over areas which know high cloudiness. The latter observes the Earth on a daily basis, but under a large range of sun-target-sensor geometry (up to 55° off-nadir viewing angles) and at a much coarser spatial resolution (250m to 1km). This low resolution results in high heterogeneity of the landscape included in image pixels, which are more often than not composed of a mixture of different eco-agrosystems.

Since May 2004, the FORMOSAT-2 Taiwanese Earth observing system is the only one that provides with high spatial resolution images with a daily revisit capability. As part of the SudMed project, one of the first time series of FORMOSAT-2 images has been acquired over the semi-arid Al Haouz/Tensift plain since November 2005. Along with these acquisitions, an experimental data set has been collected during the 2005-2006 agricultural season. This communication aims at presenting this experiment, followed by a first analysis of the potential of FORMOSAT-2 time series for agrometeorological study of semi-arid areas.

2. THE FORMOSAT-2/TENSIFT EXPERIMENT

2.1 The FORMOSAT-2 Earth observing system

FORMOSAT-2 is the first Earth observing system developed and successively launched by the National Space Organization of Taiwan (NSPO). It is operational since May 2004 onto a sun-synchronous orbit, with onboard the Remote Sensing Instrument (RSI). RSI provides high spatial resolution images (8m in the multispectral mode) in 4 narrow spectral bands ranging from 0.45 μm to 0.90 μm (blue to near-infrared). Unlike other systems operating at high spatial resolution (ASTER, Landsat, SPOT-HRV...), FORMOSAT-2/RSI can observe a particular area every day with the same viewing parameters (i.e. with a constant incidence angle). More information can be found at <http://www.nspo.org.tw/>.

2.2 Space Time Characteristics and Processing of Formosat-2 Images over the Marrakech/Al Haouz Plain

FORMOSAT-2/RSI acquisitions have been scheduled for 1 year, November 2005 to November 2006, with a nominal repetitivity of 4 days during the agricultural season (November to June), then 6 days. The size of the scenes is 24 km along-track and 27 km cross-track, centred around 7°35'W x 31°40'N (see figure 1 in the appendix). The figure 2 summarises the status of the set of images collected from November 2005 to May 2006, which will be used in this communication. During this 7-month period, the RSI instrument keeps a nearly constant incidence angle ($18^\circ \pm 1^\circ$ from nadir, viewing to the west across track). The slight variation of viewing parameters was due to satellite orbital drift and correction (acquisition times varied from 10:27 to 10:32 during the same period). About 50 images were acquired from November 2005 to May 2006, amongst which 24 has been retained for this communication. The

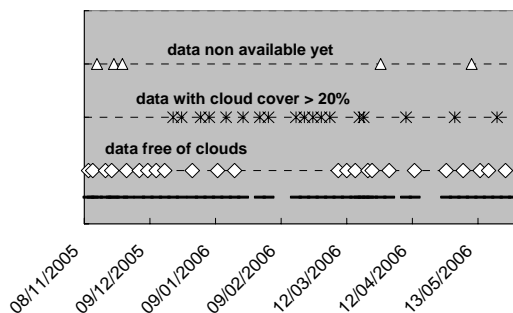


Figure 2. Status of FORMOSAT-2/RSI images collected between November 2005 and May 2006 over the Marrakech/Al Haouz plain. The bottom line is an indicator of the continuity of acquisitions.

others were eliminated because the main area of interest (see fig.1 in the appendix) was contaminated by clouds or because no data were available for atmospheric correction. From figure 2, it can be noticed:

- Some failures in the programming (end of January, beginning of February, beginning and end of April).
- A lack of cloud-free data between mid-January and mid-March due to these failures and high cloudiness.

SPOT-Image has provided us with FORMOSAT-2/RSI images in level 1A (internal radiometric processing, no geometrical correction).

Images registration was performed using a two-step procedure: 1) absolute geolocation of one of the first image of the time series (acquired December 2005 the 16th) against a set of ground control points collected with global positioning system; 2) superimposition of other images to this reference image using an autocorrelation algorithm. At the present time, this scheme is still being under development and the result is not totally satisfactory (shift in superimposition by on average 1 pixel with maximum errors of 2-3 pixels at image corners). However, given the conditions prevailing here (frequent imagery at a high spatial resolution acquired with the same incidence angle over a nearly-flat area), it is expected to reach a nearly perfect registration and superimposition of images.

High repetitivity of observations with constant viewing parameters will also allow enhanced radiometric correction. Indeed, illumination conditions (sun location) slowly and continuously varies over short period (10 days), during which the consistency of land surface can also be supposed, excepted in case of exceptional events such as floods or storms. Under these assumptions the atmospheric status – cloud-free, cloudy, hazy, with a high aerosol load... – is the principal cause of the variations of the radiances recorded by the sensor. It will be therefore possible to use one image as a reference for the correction of adjacent images in a time series. This is illustrated in the case of 3 images successively acquired March 12, 16 and 18, 2005 (figure 3 in the appendix): a visual examination of the 3 images together makes easy the detection of cloudy and shadowed areas (at northwest the 16th and at southeast the 18th); and the temporal stability of bidirectional surface reflectance (fig. 3d in the appendix) would allow a refined identification of thresholds applied in automatic detection algorithms. The same idea is at the basis of the method proposed by Hagolle et al. (this issue) for the inversion of aerosol content used for atmospheric correction.

2.3 Region of interest and experimental data

FORMOSAT-2/RSI images include the eastern part of the Al Haouz plain and the surrounding ‘*Jbilet*’ hills and foothills of the High-Atlas mountain range (fig. 1 in the appendix). This region is located in the eastern part of the Tensif basin, Central Morocco, 40 km east of the Marrakech city. In the plain the climate is of semi-arid continental type, with low and irregular rainfall (~240 mm/year), temperatures rather low in winter and very high in summer, and a very high evaporative demand (~1500 mm/year). The southern High-Atlas mountain range, which culminates up to 4000m above sea, knows much larger precipitation (up to 800 mm/year). It is the region’s water bank, which supplies several big irrigated areas in the plain and has a major contribution to ground water recharge.

The main irrigated areas are managed by a regional public agency – ORMVAH: *Office Régional de Mise en Valeur Agricole du Haouz* – which is in charge of irrigation water distribution. In these areas, dam water is transferred from an adjacent basin (*Tessaout* water catchment) through a main channel, and after that distributed into regular irrigation units through a secondary network of concrete channels. This network crosses over the old system which firstly supplies other areas through traditional irrigation channels (*Seguias*) connected with oadis and rivers of the High-Atlas foothills. This traditional system is operating during flood events. Ground water is also used for irrigation by the mean of pumping stations, in a proportion which is difficult to know.

This organisation results in a complex agricultural landscape (fig.1 in the appendix), with a large heterogeneity in the field size as well as agricultural practices. Dominant crops are cereals, mostly wheat, fallows and orchards (mainly olive trees); additional land classes include forages (mainly alfalfa) and vegetable crops. The landscape appears rather uniform with larger fields (3-4 ha) within the irrigated areas managed by ORMVAH, while other areas display a more patchy landscape with fields of lower size.

During the 2005-2006 season, an important experiment has been set up in the perspective of developing tools for improving agricultural water management. Two types of information were collected on numerous plots spread over the entire FORMOSAT scene: 1) surface reflectances of invariant areas, recorded with a handheld radiometer for testing the quality of atmospheric correction, and 2) information on crop type, to be used for calibrating and validating land cover mapping algorithm. Additional data for crop and water balance modeling has been collected at the center of the R3 irrigated area which is managed by ORMVAH (figure 4). The whole irrigated area covers 2800ha with dominant wheat crops (see Duchemin et al. 2006 for a full description). The experimental data set acquired on this area is detailed in figure 4. It includes information on agricultural practices (ploughing, sowing, irrigation, fertilisation, weed and pest controls), estimates of soil and vegetation biophysical variables (soil moisture and texture, leaf area index, wheat biomass and yield), and automatic measurements for the monitoring of surface fluxes.

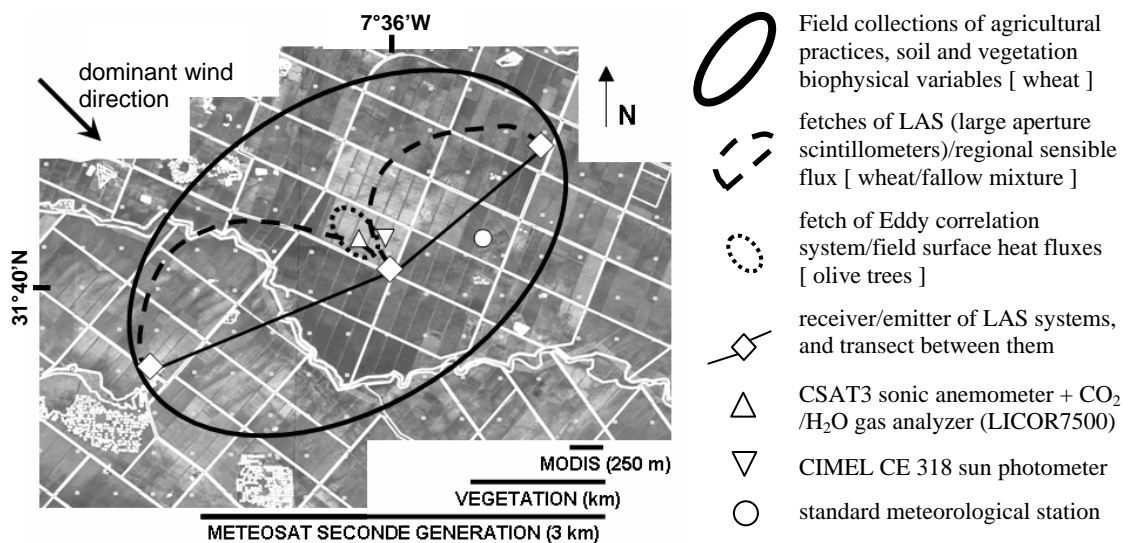


Figure 4. Details of the experimental data set collected at the center of the R3 irrigated area.

3. POTENTIAL OF FORMOSAT-2/RSI IMAGERY FOR AGROMETEROLOGICAL STUDIES

3.1 Land cover

There is an increasing need to precisely classify land cover. This information is required in planning and policy development as a basis for land use statistics at all levels. It is a prerequisite for monitoring, modelling and environmental change studies. Remote sensing has become a common and effective method for the description of land cover (Rogan et al. 2004). The synoptic coverage of satellite imagery and the relative ease of automated analysis have led to widespread mapping of the Earth through remote sensing.

However, methodology based on one or few images are suffering from limitations since: 1) there is usually some overlapping in the spectral response of the different classes; 2) the intra-class variability may be large as a result of different agricultural practices and natural changes. In this regard, the Haouz plain will offer an interesting case study. Despite the land cover is relatively simple (see section 2.2), a lot of disparity may exist for a same crop type, due to financial and organizational reasons. The characteristics of orchards can be very different depending on the age of trees (from few years to more than 100 years), the irrigation system (drip or flooding) and the spacing between stems (from 1 to 10m). Furthermore, trees are often cultivated together with another crop (usually alfalfa, wheat or barley). In the case of cereals, the farmers do not go along the same technical itinerary and there is a large heterogeneity in crop calendar, irrigation and fertilisation schedules, as well as in weed and pest control strategies. For instance, the period of sowing ranges from November to January, and the quantity of Nitrogen fertiliser applied varies from 0 to 100 kg/ha (Hadria et al. 2006). Finally, alfalfa is also a particular case: it is cultivated in small fields and the harvest is rarely done for the entire field at the same time.

For these reasons, it is difficult to use ordinary classification methods based on statistical consistency

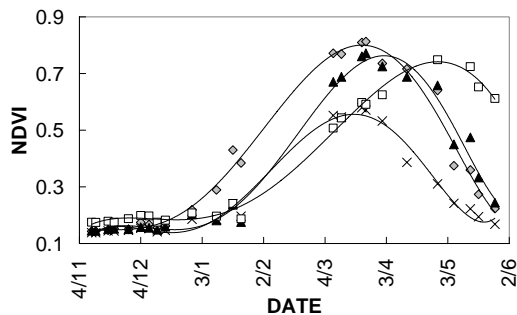


Figure 5a. NDVI time courses on annual plants: early (◇) or late (▲) sown wheat, sugar beet (□), fallow (×).

between a set of spectral signatures and a thematic class (e.g. maximum likelihood). In this context, the analysis of temporal patterns of simple surface characteristics, such as the greenness from vegetation indices, is probably more effective to map land cover. Such classification approach has already been tested at broad scale using coarse resolution satellite data for which time series were already available a few decades ago (Friedl & Brodley 1997).

The analysis of a set of 8 TM images acquired the same year over the same region has shown the potential of this approach at a high spatial resolution (Simonneaux et al. 2006). However, this study has only allowed the distinction of the following - broad - land cover classes: bare soils, annual crops, trees, annual crops mixed with trees. Thanks to the higher spatial and temporal resolution of FORMOSAT-2/RSI, it will be possible to gain both accuracy and precision in the description of land cover. In particular it is expected to discriminate additional sub-classes within annual crops (cereal, alfalfa and vegetables), by analysing the length and seasonality of the growing/senescence cycle. In this regard, the figure 5 gives some examples of NDVI time series derived on fields of different crop type. It appears realistic to separate these fields using a decision tree approach with simple criteria applied on NDVI time series (min./max. values, shape of the curve...). The directional stability of FORMOSAT-2/RSI would also facilitate the use of additional information included in surface reflectances and non normalised indices.

The size and the cost of images prevent the use of FORMOSAT-2/RSI for land cover mapping of large areas. However, a precise knowledge on a limited area could be used as a reference for regional algorithm based on coarse spatial resolution data (see BenHadj et al this issue). Information derived from FORMOSAT-2 /RSI could also serve to benchmark different land cover mapping algorithms applied at various spatial, temporal or categorical scales, i.e. for various types and groups of land cover categories (Ju et al. 2005).

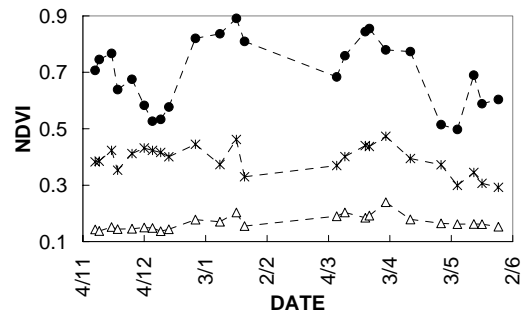


Figure 5b. NDVI time courses on 'stable' surfaces: alfalfa (●), young olive trees (*) and bare soil (△).

3.2 Water Balance and Crop Modelling

Agricultural water management and planning is a key issue for sustainable development of arid and semi-arid areas. There is thus a crucial need to develop tools for the quantitative monitoring of water and vegetation resources at a regional scale, in order to address the following – specific and complementary – issues:

- the forecasting of crop water needs and the optimisation of irrigation water distribution;
- the monitoring of actual evapotranspiration and the detection of water stress events;
- the quantification of the use and origin (ground, dam...) of irrigation water
- the estimate of crop yield and water-use-efficiency of irrigation systems.

In these regards, the scientific community has paid an increasing interest on methodologies based on agro-ecological process modelling and remote sensing (Olioso et al. 2005). Indeed, Earth observing systems provide with data regularly distributed in space and time, which can be used to have continuous simulations of the soil-plant status when coupled with crop growth and soil water balance models. Many approaches of coupling have been investigated, depending on the degree of complexity of the model and on the strategy to incorporate spatial information into it. The following illustrates extreme degrees of complexity, from the driving of simple evaporation models such as the FAO-56 one using NDVI (Er-Raki et al. this issue, Duchemin et al. 2006, Simonneaux et al. 2006) to optimisation schemes applied on more complex crop models in the perspective to calibrate some parameters of the model (Hadria et al. 2006) or to retrieve technical information as a model input (Hadria et al. this issue).

In this context, a daily survey with FORMOSAT-2/RSI would allow to improve the description of land surfaces and soil-plant systems. Data inversion schemes (Kimes et al. 2000) could be strengthened with the use of data acquired with high repetitivity, for instance by introducing constraint on the dynamics of biophysical variables (e.g. leaf area index). Therefore all approaches which have been developed to estimate yield and water balance by introducing remote sensing observations into land process models – forcing, recalibration, sequential or variational assimilation (see Olioso et al. 2005 for a review) – should know improved robustness and operationality.

A more original opportunity is also offered by the use of FORMOSAT-2/RSI time series for a direct characterisation of some aspects related to land-use. To illustrate this, we present a time composite image of red reflectances acquired from December 4 to 12 (figure 6 in the appendix). It can be seen that most of pixels displays an achromatic color of various lightness between the extremes of black and white. In these pixels the land status is still nearly constant over the 8-day period, with more or less bright surface. Indeed, this period corresponds to sowing time of cereals, which are dominant in the area of interest. Thus the grey areas are believed to mainly include bare soils with no change in their status between the 4/12 and the 12/12. Some other pixels display colours which may indicate variation of the red reflectance as indicated in the legend of figure 6. These changes result from phenomena that induce a quick variability of bare soils such as ploughing which causes an increase of surface roughness and shadows, or changes in top-soil moisture due to irrigation or drying. Fig. 7 details some of these effects from a time series of red

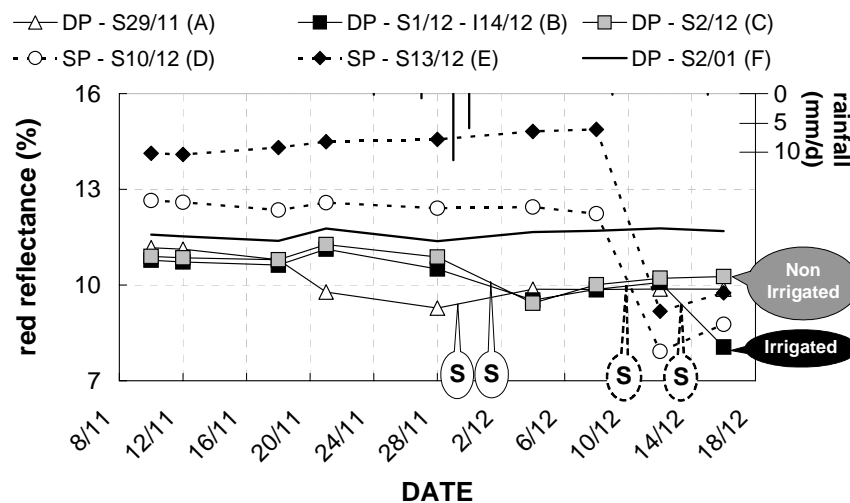


Figure 7. Time courses of red reflectances averaged on wheat fields with various technical itineraries (DP/SP = Deep/Superficial Ploughing - S=Sowing Date - I=Irrigation Date). Rainfall is displayed at the top of the figure.

reflectances averaged on wheat fields for which the technical itineraries has been recorded. There was no rainfall during this period. At the very beginning of the season, the level of reflectances appears as an indicator on the fact that fields have been ploughed at the end of the previous season to incorporate the residue in the soil (called Deep Ploughing in figure 7); after 21/11, a decrease of reflectances can be observed before sowing and at the irrigation time. These findings will help us to directly derive from remote sensing data some information related to land-use that can be critical in crop modelling (e.g. sowing date). This approach could furnish additional input in inversion scheme to better control crop and water balance models (e.g. Hadria et al. this issue). It could be useful in regional application, which generally suffers from the lack of spatially distributed data related to agricultural practices (e.g. Mo et al. 2005). In this perspective, we expect that the experimental data set collected in the R3 irrigated area will allow to validate the results obtained at high spatial resolution using FORMOSAT-2/RSI images, which in turn will help in developing algorithm to assimilate information derived from coarse spatial resolution sensors into crop and water balance models (see fig. 4).

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5. ACKNOWLEDGEMENTS

The authors acknowledge NSPO, SPOT-Image & CNES for the delivery & processing of FORMOSAT-2 images, and the AERONET network for their support in the acquisition of CIMEL sun-photometer data.

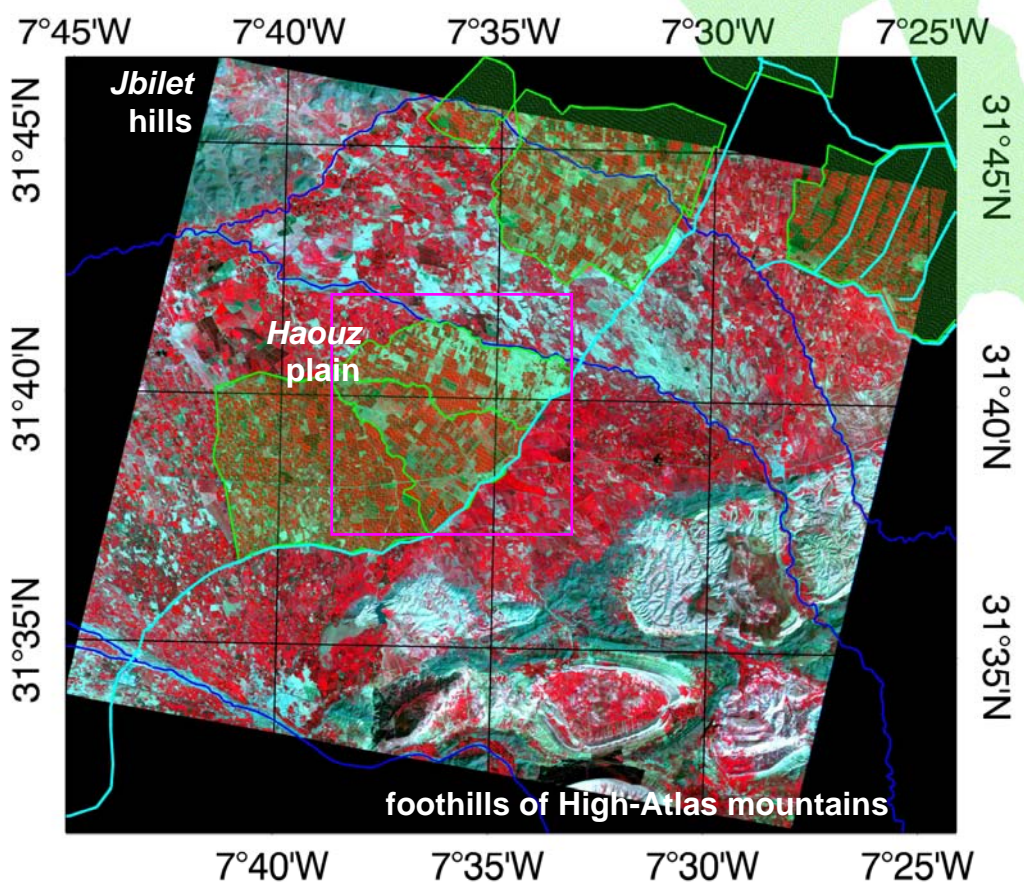


Figure 1. FORMOSAT image of March 22, 2006 (R←near infrared; G←green; B←red). Irrigated areas managed by ORMVAH are in green. Main irrigation channels and rivers are highlighted in cyan and blue, respectively. The main area of interest is delimited with the magenta square.

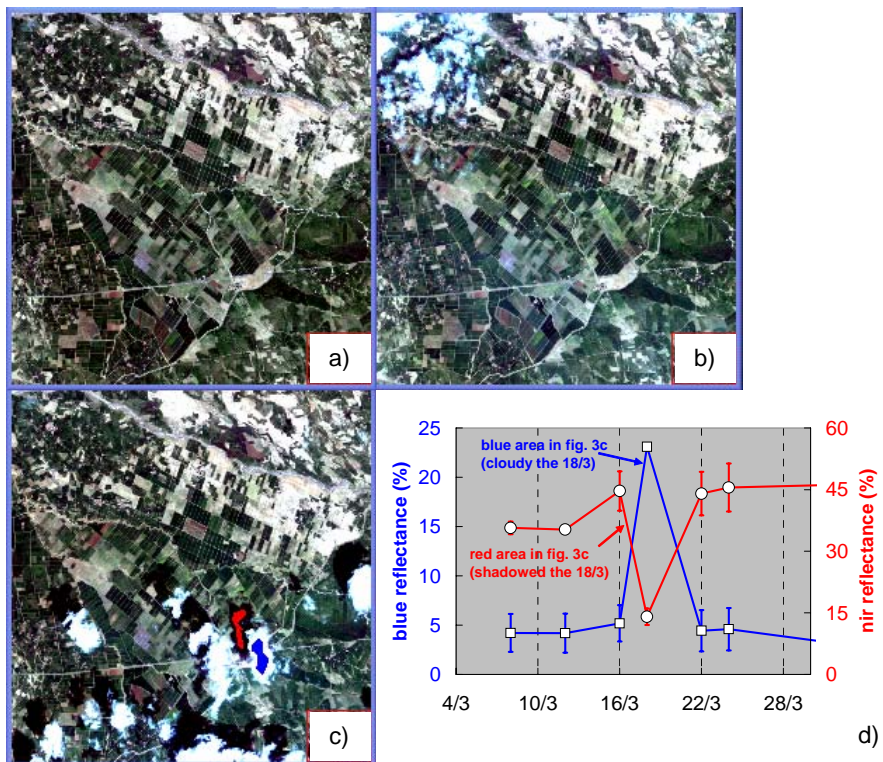


Figure 3. « True-color » FORMOSAT-2 composite images over the main area of interest (see fig.1) acquired on March 12 (a), 16 (b) and 18 (c). Figure 3d presents the time series of blue and near-infrared reflectances averaged over the blue and red areas delimited in fig.3c.

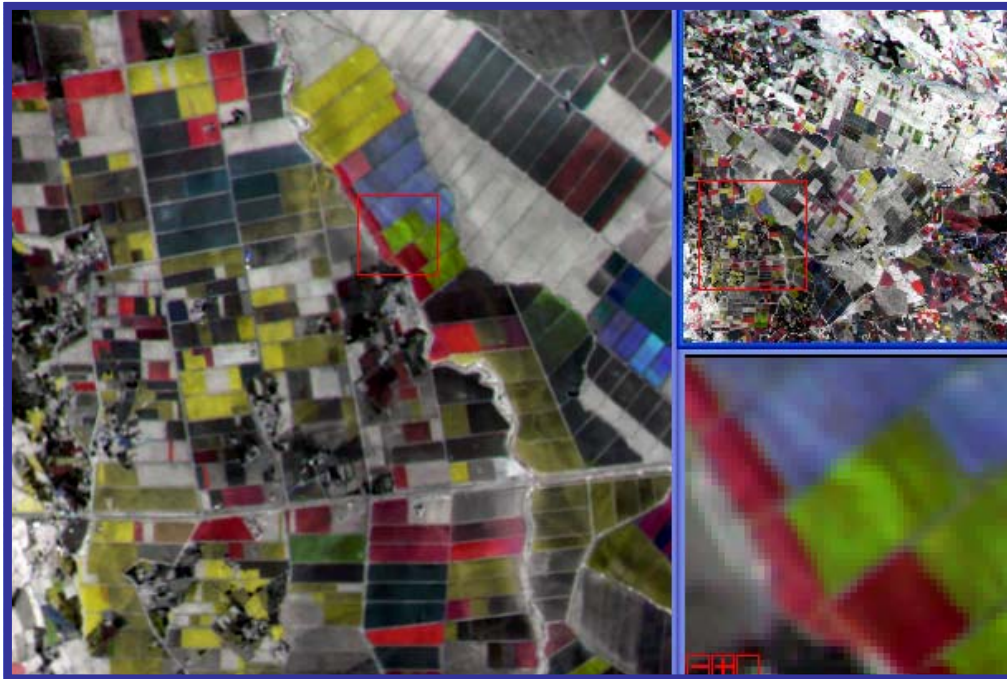


Figure 6. Time composite image of red reflectances ($R \leftarrow 4/12/06$, $G \leftarrow 8/12/06$, $B \leftarrow 12/12/06$). The top-right image displays the whole main area of interest (see fig.1), while the two other images correspond to successive zooms performed on the areas delimited by red squares. White, gray and black tones indicate stable areas with different levels of surface brightness. Coloured areas indicate a quick variation of red reflectances: decrease from 4/12 to 8/12 in red, decrease from 8/12 to 12/12 in yellow, increase from 4/12 to 12/12 in cyan to dark blue, or a peak of ρ around the 8/12 in green.