AQUATER PROJECT: THE MEASUREMENT CAMPAIGN IN CAPITANATA PLAIN OF SOIL-PLANT-ATMOSPHERE CONTINUUM


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ABSTRACT

AQUATER is a research project funded by the Italian Ministry of Agriculture, Food and Forestry Policies (2005-2008). It has the aim to develop a decision support system to integrate remote sensing information and crop simulation model to allow a best management of irrigation water at district scale. This article presents the experiment that was setup in one of the three areas of Southern Italy the project is focused on, Capitanata Plain, in order to acquire the necessary data to achieve this goal. Intensive measurements were performed in 2006 over a large agricultural region in the South-East of Italy (about 4000 km²). To capture the main processes controlling soil-atmosphere exchanges, the local climate, soil and land use were fully characterized, surface energy fluxes, vegetation biomass and structure, soil moisture profiles, surface soil moisture and soil temperature were monitored. Additional spectral plant measurements and a full characterization of physical soil parameters were also carried out. After presenting the different types of measurements, examples are given in order to illustrate the variability of soils and plant processes in the area in response to the different monitored crops: wheat, tomato and sugar beet. All the information will be used in the verification of the relationships with remote sensing data and to calibrate and validate the crop simulation model and decision support system.

Key-words: wheat, sugar beet, processing tomato, leaf area index, biomass, evapotranspiration, soil moisture, land use, soil physical properties, canopy

INTRODUCTION

The AQUATER project (Decision support systems to manage water resources at irrigation district level in Southern Italy using remote sensing information) [1] started in 2005 to develop and test methods for interpreting remote sensing (RS) data that could lead to a better evaluation of soil and vegetation functioning (biomass production, crop yield, energy balance and water budget). The proposed approach is based on the assimilation of remote sensing data into soil and vegetation simulation models. The remote sensing data used in this project are acquired mainly in the visible-near infrared (LANDSAT, IKONOS, SPOT) and micro-wave ranges (ASAR AP), not sensible this latter to cloud presence.

Crop simulation models (DSSAT, CropSyst, EPIC), mechanistic and deterministic, can help to simulate crop and cropping sequences both at field and at larger spatial scale; with information about soil, weather and crop management is possible to forecast yield, net return and a large number of output variables about water, nitrogen, and soil fertility. The user friendly interface and the link with GIS allow to extend the simulation at regional scale and to simulate the crop for a large number of years. The RS data could force the on-going running (i.e. LAI and soil water content) to improve the simulation results.

In the framework of the AQUATER project, three plains of Southern Italy were monitored: Sele river Plain, Ionic coastal Plain and Capitanata Plain. In the largest one (more than 4000 km²), Capitanata Plain, a large experiment was set up to characterize transfer of energy and water among the soil, the vegetation and the atmosphere (continuum) on the scale of a large agricultural region. This experiment included a number of ground measurements of meteorological, soil and vegetation variables at satellite overpassing. The setup of the experiment was based on the following concepts:

1. ground measurements were made on some specific fields in order to calibrate and test procedures for assimilating RS data;
2. RS measurements were made over the whole experimental area in order to extrapolate assimilation procedures to Capitanata Plain area.

In this paper, we present the measurements performed at the ground level in the Capitanata Plain in 2006 and we give an overview of the soil, crop and climatic conditions that we encountered during the experiment. In conclusion, examples of collected data, with graphs and figures, are shown.
A GENERAL VIEW OF THE AREA

Capitanata plain is characterized by six different lithological classes, defined according to the official Italian Geological Map and digitized on a GIS layer, consisting of clay, sand and gravel belonging to marine and alluvial quaternary deposits. To optimize use of water resources in irrigation requires subdividing the land into a generally small number of contiguous homogeneous zones. We applied a combined approach, linking multivariate geostatistical technique of cokriging with an algorithm of clustering, based on nonparametric density estimate, according to which a cluster is defined as a region surrounding a local maximum of the multivariate probability density function. For this purpose, the most relevant soil properties of the rooted topsoil (0-0.40 m depth) and the subsoil, measured in 1353 soil profiles and collected from different datasets of previous research project works, were submitted to the above referred data analysis. The multivariate function of spatial dependence was investigated by variography and the soil variables were interpolated on a regular grid by using the geostatistical techniques of kriging and cokriging. The application of the clustering approach to the (co)kriged variables, including the spatial coordinates after standardization of all variables to mean 0 and variance 1, produced the subdivision of the land into 8 distinct classes (Fig. 1).

The multivariate clustering essentially reproduced the spatial patterns of soil texture, characterised by most of clay and silty-clay soils. Only the two most southern clusters, 2 and 3, contain higher proportions of coarse material. The soils are sub-alkaline and alkaline with generally high levels of chemical fertility and water storage capacity.

A map of land cover for the Capitanata area has been obtained using an image from Landsat TM with the spatial resolution of 30 meters and 6 bands in the visible and near/medium infrared spectrum.

The time of the image is July 2006 and the ground truth is based on land use information provided by field survey, a data set of 2400 sample points (1600 training points and 800 to validate the resulting map, the latter randomly selected within each cover class) has been used to perform a “Maximum Likelihood” supervised classification of the remote sensing image. The scene is mostly used to agricultural crops and the land use includes 6 classes: cereal crop, orchard, vegetable crop, vineyard, urban areas and water. The cloud cover was removed from the scene by an automatic thresholding method. The overall accuracy of the classified map performed applying the traditional “Maximum Likelihood” approach is 76.2%. To improve this result we have realised a modified “Maximum Likelihood” algorithm that takes into account not only spectral information but also the spatial information computed by “Indicator Kriging” algorithm of geostatistics. This approach is based on the idea that the probability of occurrence of each class is not actually the same everywhere but depends on the pixel location [2]. The overall accuracy increases from 76.2% to 85.96%. The land cover percentage (Fig. 2) for each considered crop is:

- Cereals = 67%;
- Orchard or olive = 11%;
- Horticultural crop = 10%;
- Vineyard = 12%.

The measurement campaign covered the period April-September 2006, the whole growing season of processing tomato, and the higher evapotranspirative demand periods of durum wheat and autumnal sugar beet.

We choose to study these three crops in more details for the importance in local economy and because they have very different cultural cycles: durum wheat and sugar beet, sown in autumn and harvested in June and July-August, respectively and processing tomato, sown in April and harvested in August-September. The 6 farms selected are reported in Table I and indicated in Fig. 3; the fields were chosen large enough (more than 200 m x 200 m) to extract pure pixels also from low spatial resolution RS images.

The spatial sampling strategy allowed a good characterization of the field scale, that revealed the variability within fields, and of a regional scale as may be observed by coarse resolution sensors.
METEOROLOGICAL AND MICROMETEOROLOGICAL MEASUREMENTS

Meteorological stations network

A network of 13 agrometeorological stations is managed by a water distribution authority (Consorzio per la Bonifica della Capitanata) and daily and long-term data (1989-2006) useful for the Project have been carried out. In particular, air temperature has been measured with a steel sensor LM35Z, within a range of measurement [−40, +60] °C and a precision of 0.3 °C, rainfall has been measured with an automatic sensor Campbell at minimum reading of 0.2 mm, stored automatically by a data-logger. Solar radiation wind velocity and humidity have been measured as well.

Agrometeorological, micrometeorological and radiometric variables

The experimental campaign of 2006 season has been carried out in two farms (Forte and Mazzilli) on sugar beet and tomato crops, respectively. A summary of the agrometeorological, micrometeorological and radiometric variables with the relative measurement periods for the two crops are shown in Table II.

The agrometeorological measurements were performed approximately at the middle of two fields by standard agrometeorological stations, with 10 s intervals and averaging time of 1 hour by a CR10X (Campbell Sci., Shepshed, UK) data logger. Air temperature and vapour pressure were acquired at two levels: 0.75 and 3.30 m above the ground using two thermo-hygrometers (MP100A, Rotronic, UK). To measure the wind speed profile, this variable has been acquired at 4 levels (0.68, 1. 1.70, 3.30 m) by means of combined anemometers, with the wind direction recorded only at the top level. Rainfall was recorded using a tipping bucket rain gauge. Global radiation was measured with a pyranometer (LI200X), and PAR radiation with a quantum sensor (Li-190SB).
Table I. Specific information of the investigated fields.

<table>
<thead>
<tr>
<th>Farmer</th>
<th>Crop</th>
<th>Field number</th>
<th>Size (ha)</th>
<th>Coordinates of the central point</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lat. N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>4</td>
<td>41 30 12</td>
</tr>
<tr>
<td></td>
<td>Sugar beet</td>
<td>2</td>
<td>31</td>
<td>41 32 06</td>
</tr>
<tr>
<td></td>
<td>Durum wheat</td>
<td>2</td>
<td>7</td>
<td>41 32 16</td>
</tr>
<tr>
<td></td>
<td>Sugar beet</td>
<td>2</td>
<td>10</td>
<td>41 32 04</td>
</tr>
<tr>
<td></td>
<td>Tomato</td>
<td>3</td>
<td>10</td>
<td>41 39 15</td>
</tr>
<tr>
<td></td>
<td>Sugar beet</td>
<td>3</td>
<td>14</td>
<td>41 39 16</td>
</tr>
<tr>
<td></td>
<td>Tomato</td>
<td>3</td>
<td>15</td>
<td>41 36 38</td>
</tr>
<tr>
<td></td>
<td>Durum wheat</td>
<td>5</td>
<td>23</td>
<td>41 40 46</td>
</tr>
<tr>
<td></td>
<td>Sugar beet</td>
<td>4</td>
<td>15</td>
<td>41 36 80</td>
</tr>
<tr>
<td></td>
<td>Tomato</td>
<td>4</td>
<td>11</td>
<td>41 40 34</td>
</tr>
<tr>
<td></td>
<td>Tomato</td>
<td>5</td>
<td>18</td>
<td>41 40 38</td>
</tr>
<tr>
<td></td>
<td>Durum wheat</td>
<td>6</td>
<td>10</td>
<td>41 22 24</td>
</tr>
</tbody>
</table>

Reference system: UTM WGS 84; the coordinates are expressed in degrees, minutes and seconds.

Net radiation was measured by means of net radiometers (model Q*6), placed 1.45 and 1.60 m above ground. The soil heat flux was measured using heat flux plates placed at 0.1 m depth in the soil: these first two micrometeorological variables were collected by a CR10X data logger at a frequency of 0.1 Hz and stored as 1 hour average. Sensible heat flux was measured by means of a tri-axial sonic anemometer placed 1.5 - 2 m above the top of the canopy, coupled to a H2O/CO2 fast analyser (Li-Cor 7500, USA) to measure latent heat and carbon dioxide fluxes. The sonic data were acquired at a frequency of 10 Hz with a 1 hour averaging period. The sensible and latent heat fluxes were determined by the eddy covariance technique using a specific program. This instrument was installed inside the internal boundary layer more than 100 meters from the upwind edges of the fields, fulfilling all requirements of turbulence theory which is the basis of the eddy covariance method. All the instruments were calibrated and inter-compared before and after the experiment.

The infrared surface temperature along the four cardinal points has been measured by means of a infrared temperature sensor (IRR PN, Apogee Instruments Inc.) with a 1 hour time step, the same time step of the reflected and incident radiations in the visible/near infrared wavelengths (indicated in Table II) acquired using a 4 channel radiometer light sensor (SKR 1850, Skye Ins., UK). These latter measurements have been used to calculate the Normalised Difference Vegetation Index (NDVI) which in combination with the surface temperature is well suited to monitoring vegetation status, soil surface moisture conditions, drought and crop yield.

All collected data can be used for monitoring the meteorology of the experimental sites, to collect the suitable inputs for running simulation models of soil-crop-atmosphere continuum and to have ground measurements useful for calibrating and testing procedures for assimilating RS data. In particular, since one of the aims of the project is to define the water status of the crops, then an estimation of the actual evapotranspiration (ETa) is needed. This latter variable, directly measured by the eddy covariance technique, has been also calculated using the Penman-Monteith (PM) model [3][4] for which all required variables were available by hourly field measurements. The comparison measured/simulated ETa is well suited for verifying the chance of using the simulation model (PM) for a gap-filling of the missing ETa data due to technical problems in the acquisition system, beyond to be a confirmation of the strength of PM model. Moreover, relationships between vegetation indexes and micrometeorological variables could be investigated for testing the integration of these kinds of measurements, considering that radiometric measurements are typically acquired by means of sensors installed on board satellites.

Table II. Agrometeorological, micrometeorological and radiometric variables acquired for sugar beet and tomato crops

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>Sugar beet (Farmer: Forte)</th>
<th>Tomato (Farmer: Mazzilli)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agrometeorological</td>
<td>Air temperature, Rain, Wind speed and direction, Relative humidity, Global radiation, PAR</td>
<td>9 April → 24 May</td>
</tr>
<tr>
<td>Radiometric</td>
<td>- IR surface temperature</td>
<td>9 April → 24 May</td>
</tr>
<tr>
<td></td>
<td>- Reflected radiation at λ=561, 662, 830, 719 nm</td>
<td>9 April → 24 May</td>
</tr>
<tr>
<td></td>
<td>- Incident radiation at λ= 560, 661, 830, 719 nm</td>
<td>9 April → 24 May</td>
</tr>
</tbody>
</table>
PLANT MEASUREMENTS

In the 12 fields reported in Table I, crop management (tillage, sowing, irrigation, fertilization, and harvest) have been recorded (date and type). At every SAR satellite overpassing (15 measurements from March to August) plant (and soil) measurements were carried out. In particular, in each field and for three samples for each field, were measured:

- Plant density: the number of plants staying in 1 linear meter for wheat, 2 meters for beet and tomato were counted and referred to square meter.
- Plant height: were measured on 10 to 20 individual plants, at top of the canopy.
- Fraction cover: a measurement of the percentage of soil covered by the canopy with photo image analysis.
- Phenology: the main phenological stages were determined by marking three plants per field.
- Leaf Area Index: was performed using two different methods, (six measurements at random georeferenced points within each field): (i) LiCOR LAI2000, that measures the blue light (320-490 nm) in 5 concentric cones (with 148° field of view); (ii) AccuPAR linear PAR/LAI ceptometer, which estimates green LAI from the photosynthetically active radiation (PAR) measurements in the waveband from 400 to 700 nm.
- Plant biomass: was performed including fresh biomass, dry matter (in oven at 72°C until constant weight) and their repartition by root and leaves, only for sugar beet. The plants of 1 linear meter for wheat, 3 plants for beet and 1 plant for tomato were harvested for every sample.

At harvest, a sample of 1 square meter of plant was harvested to measure plant and fruit (root for beet) yield. The measurements at harvest were completed with wheat grain seed moisture, beet root sugar content and tomato fruit size and quality.

SOIL MEASUREMENTS

In each field of Table I, soil samples were recorded on February 2006 at 0-0.4 m depth and main chemical and physical characteristics were determined (Table III).

In order to survey soil moisture at every SAR satellite overpassing (13 measures for sugar beet, 7 for wheat and 9 for tomato) the soil water content was performed using thermo-gravimetric method at three depths (0 – 5 cm; 0 – 20 cm and 21 – 40 cm). Soil samples were immediately weighed and dried in a ventilated oven at 105°C, until constant weight and the moisture was referred to volumetric base.

The volumetric soil moisture content was also measured by means of a 16 cm long TRIME-FM probes by IMKO, which returns values using the TDR (Time Domain Reflectometry) technique. Several measurements were carried out by inserting the probe vertically in the soil around the sampling points. Mean values per field were estimated by averaging the acquired measurements. The soil density was determined at the same time intervals. It was measured using Kopecky’ rings (diameter = 5 cm; height = 5 cm) for sampling undisturbed soil. Density was determined after drying the undisturbed soil samples. In the field 5, on tomato crop and close to the agrometeorological station, soil water content was continuously (from the flowering stage until harvest) monitored by using TDR probes at three depth (15, 30 and 45 cm). The probe signals were controlled by a TDR-100 (Campbell Sci.) and stored every hour throughout a CR1000 data logger.

The soil moisture and density measurements represent the input data to the soil water balance for estimating the $ET_a$ at different time scales: daily (in the case of TDR measurements) and weekly (thermo-gravimetric method).

Moreover, in the field number 5 (Table IV), undisturbed soil cores (diameter = 8 cm and height = 8 cm) were collected at the soil surface (0 – 0.4 m) to evaluate saturated hydraulic conductivity ($K_s$), bulk density ($\rho_b$) and some points of the drying water retention function close to saturation, under a range of pressure head from 0 to -100 cm, by a hanging water column apparatus. Saturated conductivity was determined with constant-head method [5]. The retention curve (RETC) code [6] was used to fit the paired $\theta$-$h$ data.

The soil water content was also measured along the soil profile by the Frequency Domain Reflectometry (FDR) method. In particular, in 5 locations of field n. 5 (tomato) the Diviner 2000 instrument (Sentek Pty. Ltd., South Australia) was used for measuring soil water content, into PVC access tubes in the ground, by over multiple depths (at 10 cm intervals) in the soil profile (130 cm) using the probe length of 160 cm. The parameters of the Mualem-van Genuchten model were used to apply the finite difference solution of Richards equation and to simulate water transport (i.e. CropSyst model).
Table III. Chemical and physical characteristics of the 6 monitored fields (0-0.4 m depth). The field numbers are explained in Table I.

<table>
<thead>
<tr>
<th>Field number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type (a)</td>
<td>Clay</td>
<td>Silty-Clay</td>
<td>Clay</td>
<td>Clay</td>
<td>Clay</td>
<td>Clay-Loam</td>
</tr>
<tr>
<td>Field capacity (m$^3$ m$^{-3}$) (b)</td>
<td>0.407</td>
<td>0.430</td>
<td>0.414</td>
<td>0.482</td>
<td>0.409</td>
<td>0.332</td>
</tr>
<tr>
<td>Wilting point (m$^3$ m$^{-3}$) (c)</td>
<td>0.235</td>
<td>0.243</td>
<td>0.235</td>
<td>0.247</td>
<td>0.217</td>
<td>0.198</td>
</tr>
<tr>
<td>Organic matter (%)</td>
<td>1.83</td>
<td>1.97</td>
<td>1.65</td>
<td>1.53</td>
<td>1.42</td>
<td>2.82</td>
</tr>
<tr>
<td>Total nitrogen (‰)</td>
<td>1.00</td>
<td>1.22</td>
<td>0.73</td>
<td>1.03</td>
<td>0.38</td>
<td>2.32</td>
</tr>
</tbody>
</table>

(a) USDA classification
(b) Soil water content at -0.33 MPa (Richard’s plate)
(c) Soil water content at -1.5 MPa (Richard’s plate).

Table IV. Hydraulic properties of the field number 5 (0-40 cm) and parameters of Maulem-van Genuchten model estimated with RETC code.

<table>
<thead>
<tr>
<th>Field number</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil type (a)</td>
<td>Clay</td>
</tr>
<tr>
<td>$K_s$ (cm day$^{-1}$)</td>
<td>3121.1</td>
</tr>
<tr>
<td>$\rho_b$ (gr cm$^{-3}$)</td>
<td>0.85</td>
</tr>
<tr>
<td>$\theta_s$ (b) (c)</td>
<td>0.476</td>
</tr>
<tr>
<td>$\theta_{10}$ (b) (c)</td>
<td>0.422</td>
</tr>
<tr>
<td>$\theta_{20}$ (b) (c)</td>
<td>0.388</td>
</tr>
<tr>
<td>$\theta_{40}$ (b) (c)</td>
<td>0.351</td>
</tr>
<tr>
<td>$\theta_{70}$ (b) (c)</td>
<td>0.323</td>
</tr>
<tr>
<td>$\theta_{100}$ (b) (c)</td>
<td>0.306</td>
</tr>
<tr>
<td>$\theta_t$ (b) (c)</td>
<td>0.150</td>
</tr>
<tr>
<td>$\alpha$ (cm$^{-1}$) (b) (c)</td>
<td>0.113</td>
</tr>
<tr>
<td>n (-) (b) (c)</td>
<td>1.3</td>
</tr>
</tbody>
</table>

(a) USDA classification
(b) $\theta_s$ (cm$^3$ cm$^{-3}$)
(c) Value estimate with RETC code

SOME ILLUSTRATIONS

All the data collected in this first measurement campaign have been verified and stored in a data-base.

An example of the meteorological information is reported in Fig. 4, where the trend of air temperature and rain at hourly scale for the two selected crops is shown: in correspondence of the day of the year (DOY) 144 all instruments have been moved from sugar beet to tomato field on which the period of measurement has been longer, from the flowering to harvest.

In Fig. 5 the actual evapotranspiration ($ET_a$) of sugar beet measured by means of the eddy covariance technique is compared to the $ET_a$ modelled using the Penman-Monteith model: simulated values were in good agreement with the measured data, so they can be used for the gap-filling in any period of the growth season [4]. The same analysis has been done for tomato crop, giving good results at hourly and daily scale (data not shown).

![Fig. 4 - Crop season 2006: hourly air temperature and rain measured on sugar beet (DOY: 103 – 144) and tomato (DOY: 144 – 248) (DOY = Day of Year).](image1)

![Fig. 5 - Hourly actual evapotranspiration of sugar beet 2006: comparison between simulated and measured data obtained by Penman-Monteith (PM) model and eddy covariance technique respectively. Gap-filling of missing data by means the PM model between DOY 119 and DOY 130 is shown, while from DOY 131 to 138 there are only measured values.](image2)
The daily trend of soil moisture during the crop season let to know if plants experienced a soil water stress during crop cycle. As illustrated in Fig. 6, the soil water content for the tomato crop of field n. 5 was never below the wilting point (0.217 m$^3$ m$^{-3}$) for the three surveyed layers. The water scheduled by the farmer with drip irrigation method ensured a good water availability for the tomato during the whole crop cycle.

For each crop and field the plant biomass and the marketable yield were measured, both as fresh and dry matter. The increase in biomass was followed during the crop season, as well as the yield formation. As an example, the fresh tomato fruit increase of three fields is reported in Fig. 7. The different behaviours can be explained by different sowing times and crop management.

In the Fig. 8 we show the temporal variation of soil water content along the soil profile (0 – 130 cm in depth) obtained with the Diviner 2000 instrument during the crop season. As expected, large differences were observed during the crop season in the topsoil (0 – 50 cm) and relatively constant water content below the 90 cm. Due to irrigation/infiltration, evaporation, redistribution and root water uptake, the dynamics of soil water is clearly evident in the root zone (first 40 – 50 cm) and practically negligible below the 90 cm.

![Fig. 6 – Daily soil water content (% in volume) measured by the TDR methods at three soil depths during the tomato crop season (field n. 5).](image1)

![Fig. 7 – Tomato fresh fruit weigh increase over time. Vertical bars represent the standard deviations.](image2)

![Fig. 8 - Temporal variation of soil water content during the crop season observed along the soil profile (0 – 130 cm) with Diviner 2000.](image3)
CONCLUSIONS

The AQUATER project measurement campaign provided a large data-set of truth ground (soil and plants) over an agricultural area in the Mediterranean climate. Most aspects of energy and mass exchanges between soil, plants and the atmosphere were documented. The AQUATER data-set also includes also remote sensing images (SPOT-HRG, ENVISAT-ASAR and LANDSAT TM).

This data-set will be used for testing crop simulation models and to verify relationships with remote sensing information, especially multitemporal SAR images.

As examples, several works are currently in progress and some results are already available: estimation of land use using an algorithm processing remote sensing data [2]; assimilation of ASAR data into a simulation crop model [7]; retrieval of Leaf Area Index using microwave remote sensing images [8]; application of a simulation model to schedule irrigation at field [9] and district scale [10].

Finally, the ground data-set will be used to assess the possibility to extract surface variables from these data and to drive crop models in order to improve water management at large spatial scale.

ACKNOWLEDGEMENTS

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