BIOPHYSICAL VARIABLES RETRIEVAL OVER RUSSIAN WINTER WHEAT FIELDS USING MEDIUM RESOLUTION

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ABSTRACT

Winter wheat production in the Russian Federation represents one of the sources of uncertainty for the international commodity market. In particular, adverse weather conditions may induce winter kill resulting in large yields' losses. Improving the monitoring of winter-wheat in Russia with a focus on winter-kill damage and its impacts on yield is thus a key challenge.This paper presents the methods and the results of the biophysical variables retrieval on a daily basis as an input for crop growth modeling at parcel level over a 10-years period (2003-2012) in the Russian context. The field campaigns carried out on 2 sites in the Tula region from 2010 to 2012 shows that it is possible to characterize the spatial and temporal variability at pixel, field and regional scale using medium resolution sensors (MODIS) over Russian fields.

Key words: Agriculture; Wheat; LAI ; Crop ; Russia.

1. INTRODUCTION

Winter wheat production in the Russian Federation (about 10% of the world wheat production) represents one of the sources of uncertainty for the international market. In particular, adverse weather conditions may induce winter kill resulting in large yield losses. Up to day and despite this critical crop information need, no monitoring method was proven satisfying enough for wheat operational monitoring in continental climates such as in the Russian Federation. The currently existing monitoring tools, such as the MARS Crop Yield Forecasting System) have indeed some shortcomings in continental climates and need to be updated.

Improving the monitoring of winter wheat in Russia with a focus on winter-kill damage and its impacts on yield is a key challenge. Thanks to the availability of medium resolution remote sensing data and the large size of the Russian fields (about 70 Ha), the monitoring at the parcel level is becoming operationally possible and could allow to monitor and estimate the yield during the growing season. Preliminary studies [1] have indeed shown that using medium resolution imagery coupled with radiative transfer models allow to grasp multi-annual seasonal variability of winter wheat in continental climates.

A two year field campaign was carried out from August 2010 to August 2012 in the Tula region. The collected fieldwork data had several purposes: 1)the calibration of a crop model for simulating growth and yield of winter-wheat; 2) the validation of satellite derived crop maps; 3) the calibration of the soil-canopy reflectance models 4) the validation of satellite-derived biophysical variables such as green area index and the fractional coverage. This paper describes the biophysical satellite data retrieval and presents the corresponding results together with the fields measurements results. In particular, the objectives of this study were *(i)* to retrieve the Green Area Index (GAI), the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) and the Cover fraction (FCOVER) on a daily basis as an input for crop growth modeling in the Russian context and *(ii)* to characterize their spatial and temporal variability at the pixel level, field and regional scale over ten years (2003-2012) validated thanks to a two year field campaigns.

The description the geographical context of the study site and the data collected (see section 2.1) is followed by a description of the methods used to collect the data on the field (see 2.2) and to retrieve the biophysical variable from satellite data (see 2.5). The results are presented at the section 3.

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2. METHODS

2.1. Study site

The study region is located in the Tula region (about 26 000 km^2) as it is an important winter wheat producer sensitive to winter kill located 200-km south of Moscow (see Figure 1). Firstly, the Tula oblast is representative winter wheat producing region in the central part of Russia. Secondly, the region is situated close to Moscow and to Obninsk where the Space Research Institute of Russian Academy of Sciences (IKI) and by the Russian Agrometeorological Institute (AMI) are situated which facilitates the conduction of field experiments. Thirdly, the Tula region is characterized by a high diversity of soils (from podzolic soils on the north to chernozemic soils in the south) and big difference in agricultural land cover patterns: relatively small fields with dissected borders on the north and big fields with straight boundaries in the south. Therefore, the test sites are good representatives of the natural conditions diversity of the Tula region and neighbouring regions. Finally, conducting on a regular basis agricultural fields investigations was facilitated thanks to the links with the Tula regional committee of agriculture. In the frame of the special program of Russian Ministry of agriculture, they were able to collect crop data(from logistical point of view and with a permission from land owners) and meteo data thanks to a network of 20 stations. The following part describes the features of the two study test sites: Odoyev and Plavsk.

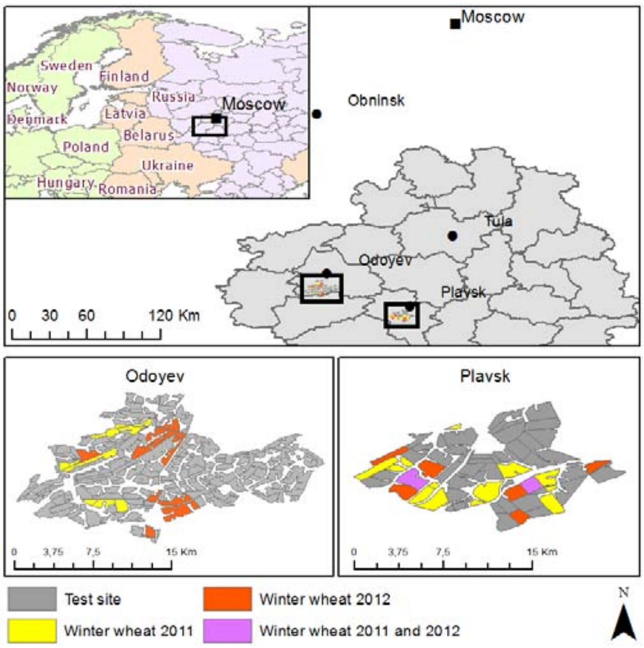

Figure 1. The test sites are located in the Tula region, major winter wheat production region, located 200 km south from Moscow. The two test sites are composed of about 10 fields for 2011 and 2012.

In **Odoyev**, the *climate* is characterized by moderately cold winter and warm summer. The long-term average air temperature is near +3.9°C. The coldest month is January with long-term average air temperature near -11.4°C. The air temperature of the warmest month (June) is near +18.1°C. Absolute minimal temperature is near -45°C, and absolute maximal air temperature is near +38°C. The period with the air temperature above 0°C is near 215 days. Active temperature sum is near 2200 degrees per year. Yearly amount of precipitation is near 600 mm with deviation from 520 to 650 mm. The maximum of precipitation is in summer. About the *relief*, the Test Area is situated on the Middle-Russian plane with absolute height near 270 m above sea level. In general the relief is dissected by river valleys, beams and gullies. The relief dissection coefficient is near 1.2. The dominant relief form is a hill with level surface and with graduate and long slopes. About the *vegetation*, the territory is situated in the forest-steppe transit zone. Forests occupy near 7% of total region. Dominant forest stands are represented by oak and birch. Herbaceous vegetation is a dominant on the bottoms of the valleys, and gullies, and on the steep slopes. Practically all level surfaces are occupied by arable lands. Dominant *soils* are grey forest soil. Soils were developed on the loess silt-clay deposits. Soils contain carbonates on the depth near 150 cm. Humus content in the ploughed horizon is near 3%. Some of the soil on slopes is eroded. Concerning the *land use*, the main crops are winter wheat (near 30%), spring wheat (near 23%), spring barley (near 17%), maize (near 4%), and oats (near 2%). Other cultivated crops are winter rye, buckwheat, pea, potato, annual and perennial grasses. The crop production is mechanized. Fertilizers are used, but not regularly from year to year. The crop yield is not very high and strongly variable from year to year.

In **Plavsk**, the *climate* is characterized by moderately cold winter and warm summer. The long-term average air temperature is near +4.2°C. The coldest month is January with long-term average air temperature near -11.1°C. The air temperature of the warmest month (June) is near +18.5°C. Absolute minimal temperature is near -43°C, and absolute maximal air temperature is near +39°C. The period with the air temperature above 0°C is near 219 days. Active temperature sum is near 2300 degrees per year. Yearly amount of precipitation is near 600 mm with deviation from 510 to 630 mm. The maximum of precipitation is in summer. About the *relief*, the Test Area is situated on the Middle-Russian plane with absolute height near 280 m above sea level. In general the relief is dissected by river valleys, beams and gullies. The relief dissection coefficient is near 1.1. The dominant relief form is a hill with level surface and with graduate and long slopes. Concerning the *vegetation*, the territory is situated in the forest-steppe transit zone. Forests occupy near 5% of total region. Dominant forest stands are represented by oak and birch. Herbaceous vegetation is a dominant on the bottoms of the valleys, and gullies, and on the steep slopes. Practically all level surfaces are occupied by arable lands. Dominant *soils* are chernozemic soil. Soils were developed on the loess silt-clay deposits. Soils contain carbonates on the depth near 110 cm. Humus content in the ploughed horizon is near 5%. Some of the soil on slopes is eroded. Land Use Concerning the *land use*, the main crops are winter wheat (near 47%), spring wheat (near 18%), spring barley (near 13%), maize (near 8%), and oats (near 2%). Other cultivated crops are winter rye, buckwheat, pea, potato, perennial grasses. The crop production is mechanized. Fertilizers are used, but not regularly from year to year. The crop yield is between 2 and 4 ton/ha, and strongly variable from year to year.

2.2. Ground measurements

Different intensive field campaigns were carried out by IKI and by AMI for calibration and validation purposes. In addition to crop type inventory along transects, IKI and AMI visited on a regular basis along two growing seasons, *i.e.* 2011 and 2012, 20 winter wheat fields distributed in two different areas (Odoyev and Plavsk as presented at the figure 1). The field measurements included the crop type, the crop stage, the Leaf Area Index then derived from hemispherical photographs and representative soil spectra. Indeed, the so-called black soil background may influence the spectral signature in the early development stages of the growth cycle, corresponding to the period of observation for the winter kill.

The following information was collected:

1. Measurements of crop total biomass and crop yield through crop cutting experiments. Together with these measurements information about crop height, crop phenological status and general condition of the field was collected as well.
2. Downward looking images of the winter-wheat fields using a digital camera equipped with a hemispherical lens (e.g. fisheye lens). These images were processed with the CAN-EYE software to obtain canopy biophysical variables (FCover, PAI and FAPAR)[2]. Unlike the LAI-2000 technique, using Digital Hemispherical Photography (DHP) allows to make the distinction between green and non-green elements directly. A minimum of 8 downward-looking pictures were taken above the canopy within an area of about 50-m of in every visited field. Each set of DHPs constituted is supposed to represent the canopy's variability and produces a single value of GAI.
3. Reflectance spectra of the crop canopy and the soil using a spectrometer.
4. Crop type distribution in the test sites (2011-2012) and following over the whole Tula region (2012 season only).

Field observations were collected for two growing seasons in 2011 and 2012. Depending on logistics and weather, the fields were visited on a weekly basis thereby alternating the visits to the two test sites. In practice field observations for each site were carried out with in a two weeks intervals.

2.3. Satellite data

The MODIS collection 5 daily reflectance products (MOD09 and MYD09)from both Terra and Aqua platforms are used in this study . These products are atmospherically and geometrically corrected and distributed. The red and near-infra-red spectral bands with a 250-m spatial resolution (MYD09GQ, MOD09GQ), were compiled in time series from 2003 to 2012. Ancillary information concerning acquisition geometry (view zenith angles (VZA), sun zenith angles (SZA) and relative azimuth angles (RAA)) are also obtained for each reflectance measurement.

2.4. Winter crop and purity mapping

As this study focus on winter wheat, winter crop masks were first derived using a dedicated methodology based on [3] and [4]. In order to identify these relevant cells, which change from year to year according to farmer's choices and rotation practices, a MODIS spatial response model to assign a value of wheat pixel purity to each cell using the methodology proposed by [5]. This pixel purity value (π) is to be taken as a proxy of the proportion of the signal which originates from areas covered by winter wheat. The real value of this proportion may be different for several reasons such as potential errors in the crop mask data, distortion of the sensor's field of view when it acquires images with high viewing angles or artefacts resulting from the resampling into the grid. As described by [6], the latter two problems change from one MODIS image to another, and are partially dealt with (as explained further) using indications from the ancillary information from VZA and obscov. Only pixel with an overall threshold of $\pi \geq 90$ % were kept.

2.5. Biophysical variable retrieval using radiative transfer inversion with neural networks

The biophysical inversion algorithm is based on CYCLOPE ([7]) adapted (as in [5]) and then parametrised over the Tula region for winter wheat. A learning database for the neural networks is constituted by simulating a wide variety of canopy reflectances with the PROSAIL model providing reflectance based on a series of input variables describing the structure of the canopy, the leaf optical properties and the background soil reflectance. In the current study, a total number of 55296 simulations were carried out based on the distribution parameters presented in the Table 2. The leaf optical properties were described using 5 parameters: the mesophylle structure parameter (N), chlorophyll (C_{ab}), dry matter (C_{dm}), water (C_w) and brown pigment (C_{bp}) contents. Water content is linked to the dry matter content in the form of green leaf relative water content (H). C_{bp} corresponds to the polyphenol pigments responsible for senescence. A brightness coefficient (B_s) describing soil background reflectance is also necessary and is obtained by selecting

Table 1. Input variable distributions used to generate the learning database

	Variable	Minimum	Maximum	Mode	Std	Class	Law
Canopy							
	GAI	0,0	15,0	2,5	2,0	6	gaussian
	ALA (°)	30	80	60	20	4	gaussian
	$CrownCover$	1,0	1,0	0,8	0,4	1	uniform
	HsD	0,1	0,5	0,2	0,5	1	gaussian
Leaf							
	N	1,20	1,80	1,50	0,30	3	gaussian
	C_{ab}	20	70	45	23	4	gaussian
	C_{dm}	0,0030	0,0110	0,0050	0,0050	4	gauss
	$Cw_{R}el$	0,60	0,85	0,75	0,08	4	uniform
	C_{bp}	0,00	2,00	0,00	0,30	3	gaussian
Soil							
	Bs	0,50	3,50	1,20	2,00	4	gaussian

a subset of soil spectra from a database. Calculating the RMSE to spectra collected on the fields allows to select 78 soils from the database. The sampling scheme consists in identifying classes of values for each variable and combine all the classes together. At end the simulation process, a total of 55296 were simulated. This dataset set is then split in two parts: to train the neural network ($\frac{1}{3}$) and to evaluate the theoretical performance ($\frac{2}{3}$). The training database was specifically located over the Tula Oblast and neighbourhood. Therefore, the latitude was constrained from 50° to 60° North and the longitude from 30° to 60° East.

3. RESULTS

3.1. Field data

The 2011 field campaign was limited by the fact that the equipment became available only by the end of April and the first field visits could be done end of May. This means that the important green up phase of winter-wheat after the winter is missing in the field measurements. The field work was carried out by two field teams the Crop-Cutting Team and the Camera and Spectrometer Team the teams synchronized the field visits as much as possible during the campaign. For the 2012 growing season the field campaign was started on time with the first field visits already before the winter on 14 October (Odoyev) and 21 October (Plavsk).

The Figure 2 shows the height measurements for 2011 (up) and 2012 (down) for both sites. The figure shows that the 2011 height growth was slightly delayed (the 1st of June, the mean height was 60 cm in 2011 and 75 cm in 2012). However, the height at the end of the growing season is relatively similar for both year (mean 80 cm) but with a higher standard deviation in 2011 probably linked to an heterogeneity growth in 2011.

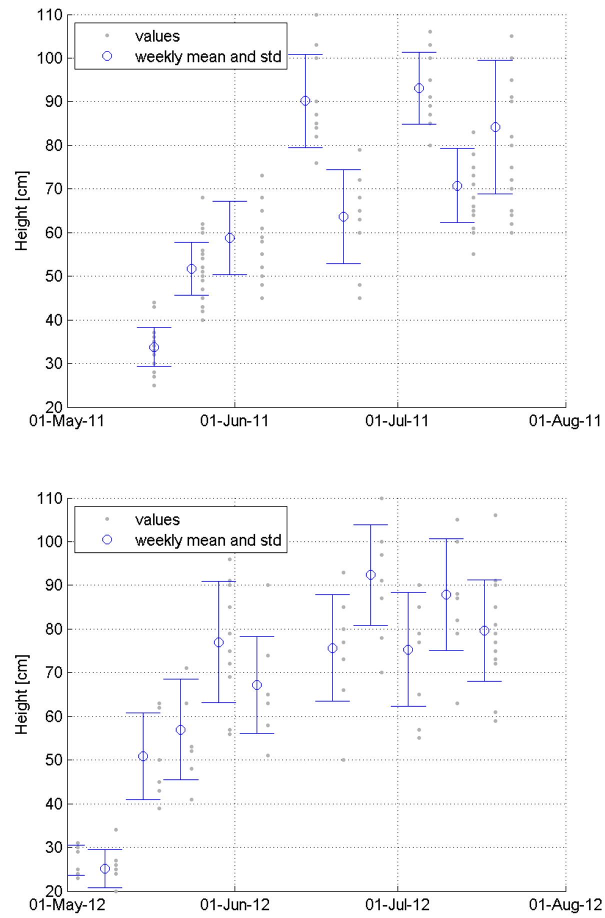

Figure 2. Height measurements on the two test sites for 2011 (up) and 2012 (down). The mean and standard deviation are calculated weekly.

The Figure 3 shows the plants density [$plants/m^2$] for 2011 (up) and 2012 (down) for both sites. The measurements from 2011 are not sufficient to make an interannual comparison even if it seems that the standard deviation was really high at the end of the 2011 growing season. For the year 2012, the density is relatively stable ending the season with a mean 580 $plants/m^2$ at the end of the growing season.

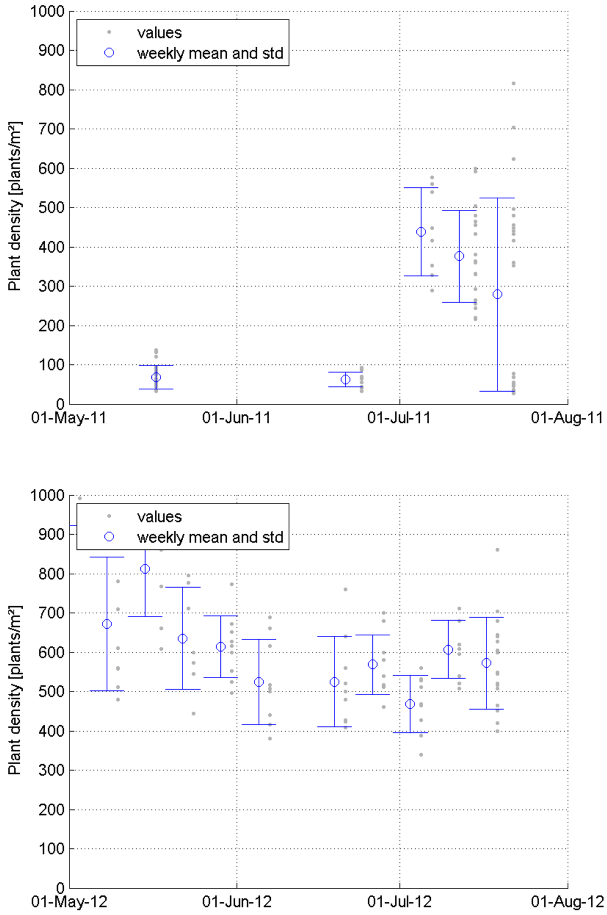

Figure 3. Plant density measured on the test sites for 2011 (up) and 2012 (down). The mean and standard deviation are calculated weekly.

Figure 4 shows the plants biomass evolution $[Kg/ha]$ for 2011 (up) and 2012 (down) for both sites. The evolution of the biomass is logically correlated with the height in the very active growing phase. Comparing the mean biomass value obtained the 1st of June indicates that the 2011 year growing was slightly delayed.

3.2. Winter crop and purity maps

The winter crop mask used in the current study (Tula region from 2003 to 2012) was validated with an overall accuracy of 82% during 2011 and 2012. Figure 5 show the purity (π in %) calculated from the obscov and the vza. The corresponding number of pixels by year with the corresponding purity is presented at table 2. Figure

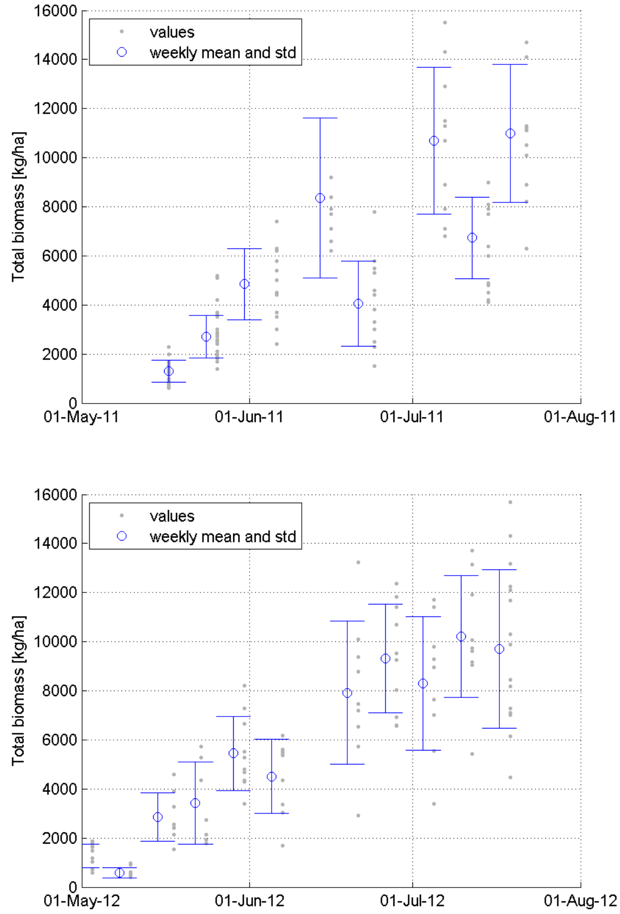

Figure 4. Biomass measured on the test sites for 2011 (up) and 2012 (down). The mean and standard deviation are calculated weekly.

5 and the corresponding Table 2 show that there is an important fluctuation from year to year. The year 2007 was particularly low with less than 6000 pixels reaching a 90% purity. This emphasizes the importance of having a robust monitoring tool to compare year to year changes.

3.3. Biophysical variables

The GAI, FAPAR and FCOVER were retrieved for all the winter wheat crop fields from 2003 to 2012 on a daily basis. Every pixel time series on a daily basis were inverted to get biophysical variables from the reflectance. This represents about 4.5 million records that were store in a database to allow further analysis. It was thus possible to examine and compare the fields at parcel level level such as presented on Figure 6 where two neighbours fields biophysical time series are presented for 2011.

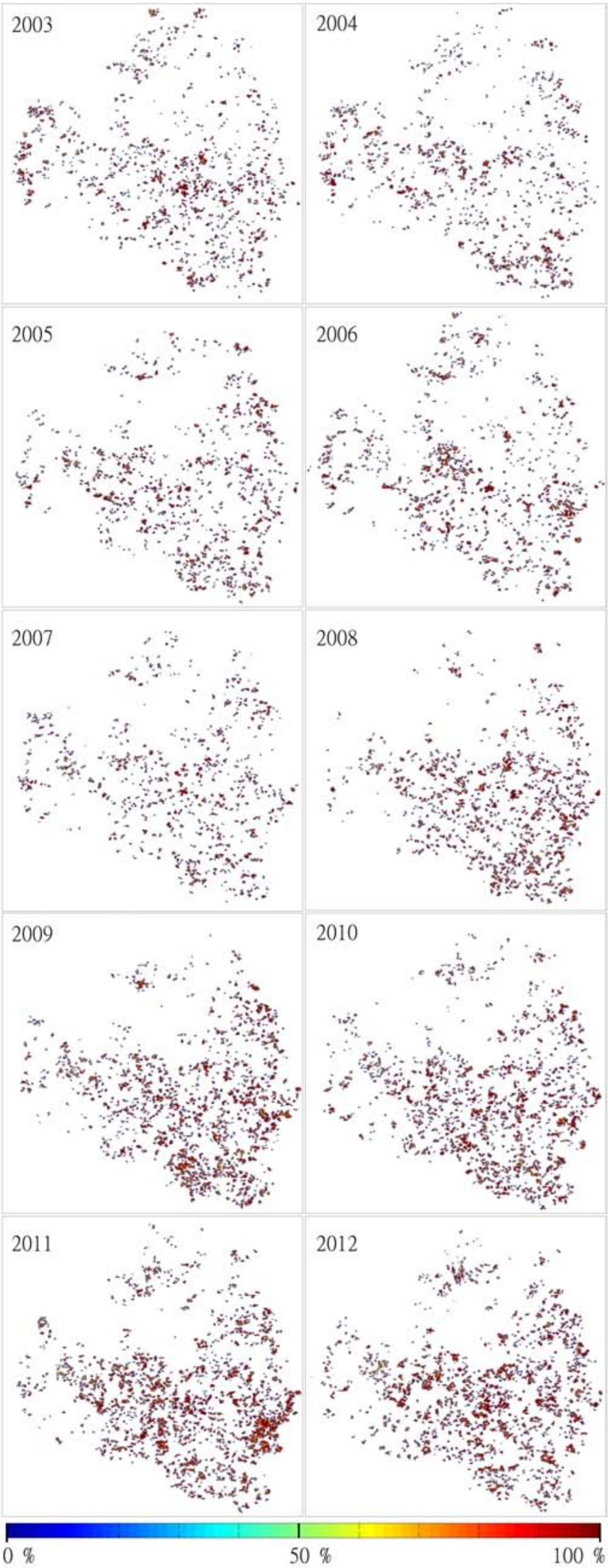

Figure 5. Winter wheat purity (π %) maps for the Tula region from 2003 to 2013 obtained from MODIS using View Zenithal Angle (VZA) and Observation cover (obscov).

Table 2. Number of MODIS pixels satisfying the corresponding purity criteria by year for the Tula region

Year	$\pi \geq 75$ %	$\pi \geq 80$ %	$\pi \geq 85$ %	$\pi \geq 90$ %
2003	12679	11193	9502	7553
2004	11139	9721	8307	6578
2005	11734	10372	8876	7160
2006	12834	11242	9618	7700
2007	9698	8553	7293	5862
2008	15054	13300	11381	9221
2009	19212	16988	14621	11796
2010	18551	16372	14016	11313
2011	23243	20570	17637	14354
2012	21410	18798	16161	13023

3.4. Validation with ground GAI

The Figure 6 shows the results obtained for two neighbouring fields during the 2011 growing season. Even for year with few cloud free acquisitions in June, the retrieved values from satellite imagery have a good coherence with the values retrieved from the fields measurements.

4. DISCUSSION AND PERSPECTIVE

This experiment highlights the critical impact of both spatial and temporal resolution for operational crop monitoring, demonstrating the gaps between nominal and effective temporal resolution due to clouds and atmospheric perturbations and the needs for multi-sensor approach or very high temporal resolution. This experiment has also shown the constraints of managing appropriate fields campaigns for remote sensing biophysical variable validation. Furthermore it opens the way to characterize the variability at the parcel level with a high temporal frequency. As it is possible over large fields using medium resolution sensor such as MODIS, the sensors such as the future Sentinel-2 combining a higher spatial resolution and temporal frequency opens the way for operational monitoring at parcel level.

5. CONCLUSION

Biophysical variables (GAI, FAPAR and FCOVER) were retrieved from multispectral reflectance daily time series for the selected grid cells using an approach combining radiative transfer modeling and neural networks over the Tula Russian region from 2003 to 2012. A CYCLOPES-adpated algorithm retrieved the variables from the MODIS instruments on-board of Aqua and Terra

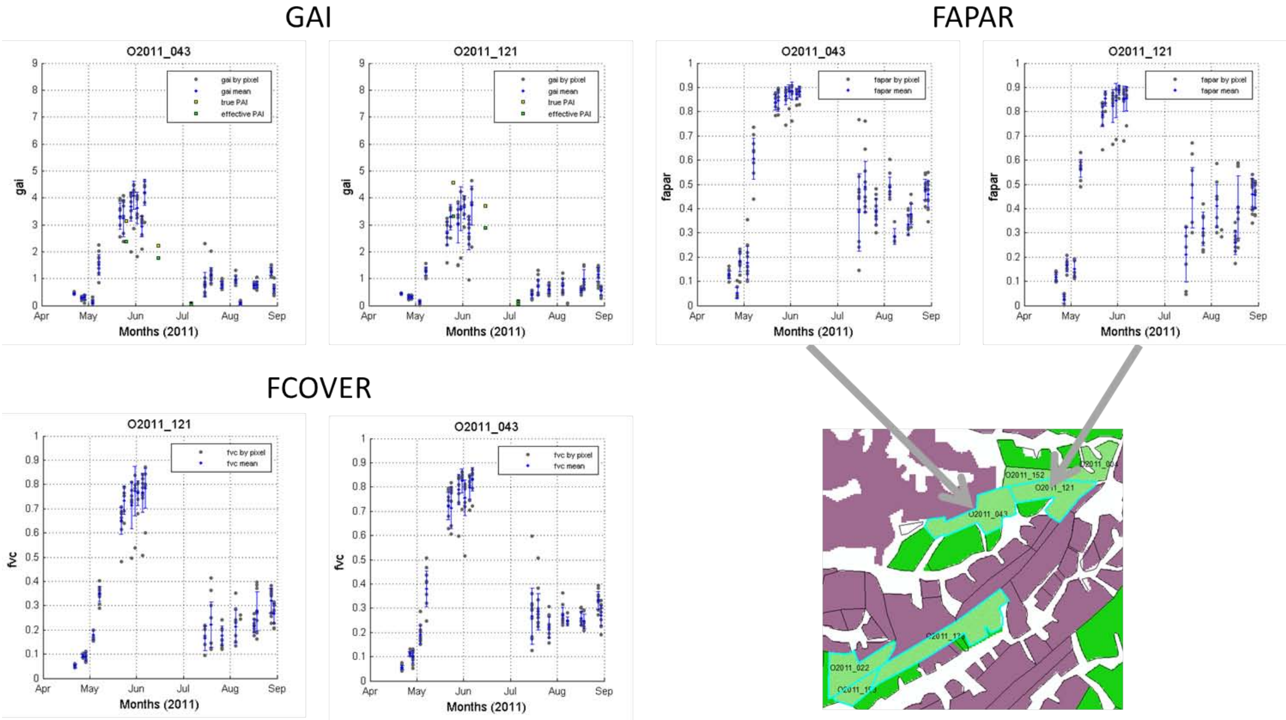

Figure 6. Example of biophysical variable retrieved for 2011 growing season for two winter wheat fields. GAI is plotted with the PAI measured from the field.

platforms and calibrated for the Tula Oblast integrating soil spectra from the field. The accuracy of the biophysical variables retrieval were then assessed using the measurements from a 2-year's fields' campaigns (2011-2012).

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