

7. DEVELOPMENT OF A TOOL TO MONITOR CROP GROWTH AND GRAIN YIELD

By: **Antonio de la Casa¹** and **Gustavo Ovando²**

The Center for Surveying and Assessment of Agriculture and Natural Resources (CREAN) is an applied research unit of the Agricultural Sciences Faculty (Department) of the Córdoba National University (Argentina). The general objective of CREAN is to contribute to the development of strategies for sustainable management of natural and agricultural resources, based on rational use, preservation and recovery of the environmental patrimony. This involves the elaboration of application programs using remote sensing information and geographic information system. CREAN plays an active role to develop new methodologies to assess desertification processes, crop yield productivity and crop geographic distribution. Furthermore the Centre provides technological support to the public and private sectors on uses and applications of meteorological and natural resources information.



Universidad Nacional de Córdoba



Facultad de Ciencias Agropecuarias



Centro de Relevamiento y Evaluación de Recursos Agrícolas y Naturales

7.1. Relevance of the topic selected

Monitoring of agricultural crops throughout the growing season may provide information to make predictions of performance before harvest time. This is important for decision making at various levels, both for logistic and commercial activities (Rizzi and Rudorff 2005).

The yield of a crop is determined by its genetic characteristics and prevailing conditions during the growing period, such as climate and weather conditions, soil fertility, pest and disease control, soil water stress and other factors affecting crop growth. The crop yield can vary widely in response to dominating conditions. By means of a mechanistic crop growth model, the expected yield for several growing conditions can be estimated (Boote *et al.*, 1998; Brisson *et al.*, 2003; Yang *et al.*, 2004). Such type of models not only simulates yield but also crop development throughout the growing cycle. The mechanistic models, however, generally require a huge set of input data which is often not readily available outside research stations. Since they also demand an extensive site-specific calibration before they can be applied, this type of model might not be very useful for developing irrigation strategies or applied to yield forecasting under practical conditions.

For planning and evaluation purposes with limited data, a more general and simpler approach is available. The functional model presented by Doorenbos and Kassam (1979), describing the relation between water stress and the corresponding productivity loss is very useful:

$$1 - \frac{Y_a}{Y_{\max}} = K_y \left(1 - \frac{ET_a}{ET_{\max}} \right) \quad \text{Eq. 1}$$

where Y_a/Y_{\max} is the relative yield; $(1 - Y_a/Y_{\max})$ the relative yield decrease; ET_a/ET_{\max} the relative evapotranspiration; and $(1 - ET_a/ET_{\max})$ the water stress or relative evapotranspiration deficit.

¹ Antonio de la Casa email: delacasa@agro.unc.edu.ar

² Gustavo Ovando email: gugovan@gmail.com

The response of yield to water stress for a given environment, is quantified through the yield response factor (K_y). The relationship between yield decline and water stress is linear as long as water stress is less than 50%. In the model, the actual yield (Y_a) is expressed as a fraction of the maximum yield (Y_{max}) that can be expected under the given growing conditions for non-limiting water conditions. ET_a refers to the actual crop evapotranspiration under the given growing conditions and ET_{max} is the evapotranspiration under the same conditions but for non-limiting water conditions.

This functional model has been implemented in various ways according to the type and availability of information used (Rojas, 2007). Raes *et al.* (2006) used a water balance procedure to estimate ET_a from meteorological information (ET_{max} and precipitation data), as well as soil characteristics relating to soil water content to calculate the crop yield loss.

Remote sensing provides extensive spatial information about the actual status of crops and it has been used to support the parameterization of crop models (Guérif and Duke, 2000). The advantages of remote sensing are being exploited in recent years to monitor vegetation and assess the impact of drought on crop yield. Caselles *et al.* (1993) used NDVI images from NOAA-AVHRR to determine, together with field data, the various components of the FAO Model productivity. Funk and Budde (2009) present a detailed breakdown of the studies on the NDVI and crop yield and sustain the desirability of tuning the relationship between drought and productivity on the basis of phenological data. De la Casa and Ovando (2007) developed a crop model to estimate the yield of maize at regional/departmental level, integrating NDVI data with phenological information.

A strategy to make yield estimation methods more robust and easily exportable is provided by the integration of remote sensing data with crop simulation models (Doraiswamy *et al.*, 2003). Moriondo *et al.* (2007) present the development and testing of a methodological framework which utilizes NDVI data and a simulation model (CROPSYST) to estimate the crop phenology. This operation relies on two main steps, the first being the computation of above-ground biomass (AGB) obtained through the use of NDVI-derived fraction of absorbed photosynthetically active radiation ($fAPAR$), which is calculated by:

$$fAPAR = b \times NDVI - a \quad \text{Eq. 2}$$

$$AGB = \sum_{i=1}^n \varepsilon_i \times fAPAR_i \times PAR_i \quad \text{Eq. 3}$$

As crop canopy cover fraction ($fCov$) could be considered similar to $fAPAR$ in corn (Edwards *et al.*, 2005) and soybean (Purcell, 2000), this expression can be rewritten as:

$$AGB = \sum_{i=1}^n \varepsilon_i \times fCov_i \times PAR_i \quad \text{Eq. 4}$$

Where ε_i and PAR_i are the radiation use efficiency (RUE, g MJ⁻¹) and the photosynthetically active radiation (PAR) at day i , respectively; n is the number of simulation days.

The second step consists of the final partition of the estimated biomass into maximum crop yield (Y_{max}), which is obtained through the use of the harvest index (HI) where HI is set to 0.47 for maize and soybean.

$$Y_{max} = AGB \times HI \quad \text{Eq. 5}$$

The actual evapotranspiration (ET_a) can be estimated using different calculation alternatives depending on the sources of information. The soil water balance was routinely used, but it needs precipitation (PP) and maximum evapotranspiration (ET_{max}) data, as well as information about the type of soil and its ability to retain water.

In a similar but more simplified way, NDVI values are considered substitutes to the transpiration rate (Funk and Budde, 2009) and therefore the FAO productivity model can be adapted according to the following expression:

$$1 - \frac{Y_a}{Y_{max}} = K_{y_i} \left(1 - \frac{\sum NDVI_a}{\sum NDVI_{max}} \right) \quad \text{Eq. 6}$$

Where $\Sigma NDVI_a$ is NDVI value accumulated during the entire cycle or each stage of development and $\Sigma NDVI_{max}$ the highest value of all fields.

Córdoba government compiles statistics of agricultural production using traditional methods based on field surveys to establish at department scale the planted/harvested area, yield and production of crops of major economic importance (SAyGA, 2010). These methods are laborious, requires field staff and they do not generate results as quickly as required by the markets (Rosenthal *et al.*, 1998).

7.2. Objective of the application

This application proposes to develop a semi-operational procedure to estimate corn and soybean yield in Cordoba Province, Argentina. The procedure will be implemented in a regional framework making use of different ILWIS routines to calculate FAO Model productivity components, with NDVI data from MODIS satellite, and local (in situ) field information.

7.3. Data collection and pre-processing

7.3.1. NDVI data

Ensure that you have unzipped the exercise data and move using the ILWIS navigator to this active working directory. Once close ILWIS and Open ILWIS again to ensure that the directory settings are correct. You can have a look at the data that is available in this folder; open the map list “sub_modis_ndvi” and display the map list as an animated sequence, using as Representation “NDVI1”. For this application 17 raster NDVI images (MODIS - MOD13Q1 16 days product, 250m, tile h12v12, ENVI format), ranging from September 2005 to May 2006 have been selected. These images were transformed to ILWIS image format and a sub map was prepared covering the region of interest. Further details are listed in table 7.1.

Raster Name	From	To	SRAD
sub_modis_ndvi_1.mpr	6-Sep-05	21-Sep-05	11.6
sub_modis_ndvi_2.mpr	22-Sep-05	7-Oct-05	16.8
sub_modis_ndvi_3.mpr	8-Oct-05	23-Oct-05	18.2
sub_modis_ndvi_4.mpr	24-Oct-05	8-Nov-05	19.8
sub_modis_ndvi_5.mpr	9-Nov-05	24-Nov-05	20.7
sub_modis_ndvi_6.mpr	25-Nov-05	10-Dec-05	21.6
sub_modis_ndvi_7.mpr	11-Dec-05	26-Dec-05	20.5
sub_modis_ndvi_8.mpr	27-Dec-05	11-Jan-06	23.1
sub_modis_ndvi_9.mpr	9-Jan-06	24-Jan-06	23.3
sub_modis_ndvi_10.mpr	25-Jan-06	9-Feb-06	19.0
sub_modis_ndvi_11.mpr	10-Feb-06	25-Feb-06	19.6
sub_modis_ndvi_12.mpr	26-Feb-06	13-Mar-06	22.2
sub_modis_ndvi_13.mpr	14-Mar-06	29-Mar-06	18.2
sub_modis_ndvi_14.mpr	30-Mar-06	14-Apr-06	17.6
sub_modis_ndvi_15.mpr	15-Apr-06	30-Apr-06	13.8
sub_modis_ndvi_16.mpr	1-May-06	16-May-06	15.8
sub_modis_ndvi_17.mpr	17-May-06	1-Jun-06	14.1

Table 7.1 NDVI images, timing details and Manfredi accumulated solar radiation (SRAD, MJ m²)

7.3.2. Administrative boundary map

The administrative boundaries have been obtained from a vector map with departmental boundaries of Cordoba Province, in drawing exchange format (DXF), imported in ILWIS and have been named “boundary”. Add the polygon file “boundary” to your active map display window, using “info off” and “boundaries only” Display Options.

7.3.3. Meteorological data

The daily solar radiation data from Manfredi meteorological station (31° 49' 12" S, 63° 46' 00" W, altitude 292 m osl) have been used, located in the central area of Córdoba. The accumulated value for each image period was calculated (see table 7.1).

7.3.4. Canopy cover fraction (fCov) measurements

Field measurements of $fCov$ were made by classification of digital photos with a maximum likelihood algorithm, as is shown in figure 7.1. Pictures for soybean and corn crops were collected during 3 years, including the 2005-2006 crop cycle, in several fields in the central region of Córdoba. They were taken vertically from a height of 1.5 m. In total 150 pictures have been classified for soybeans and corn.



Figure 7.1 $fCov$ measurements of corn, original (left) and classified results (right)

The $fCov$ values were analyzed by regression with NDVI to obtain a model which was used for both crops. The model used is:

$$fCov = 1,228 \times NDVI - 0,245 \quad \text{Eq. 7}$$

7.3.5. Departmental Crop yield data

The Agricultural Secretary of Córdoba Province supplies statistics of departmental agricultural production. They use traditional methods based on reports to establish the planting, harvesting, yield and production of crops of major economic importance in the region (SAyGA, 2010). Details are provided in Table 7.2.

ID Number	Department	Corn Yield (kg ha ⁻¹)	Soybean Yield (kg ha ⁻¹)
1	Calamuchita	7,000	2,442
2	General Roca	6,800	2,300
3	Gral. San Martín	5,500	2,150
4	Juárez Celman	6,000	2,370
5	Marcos Juárez	8,000	3,300
6	Pte. R. S. Peña	6,500	2,200
7	Río Cuarto	4,000	2,000
8	Río Primero	6,000	2,200
9	Río Segundo	7,000	2,300
10	San Justo	5,500	2,050
11	Santa María	6,500	2,400
12	Tercero Arriba	6,500	2,800
13	Unión	7,000	2,442



Table 7.2 Corn and soybean yields of main agricultural crops in Córdoba in 2005-2006 crop season

7.4. Methodology

The flow chart showing the procedure adopted to estimate grain yield is presented below in figure 7.2.

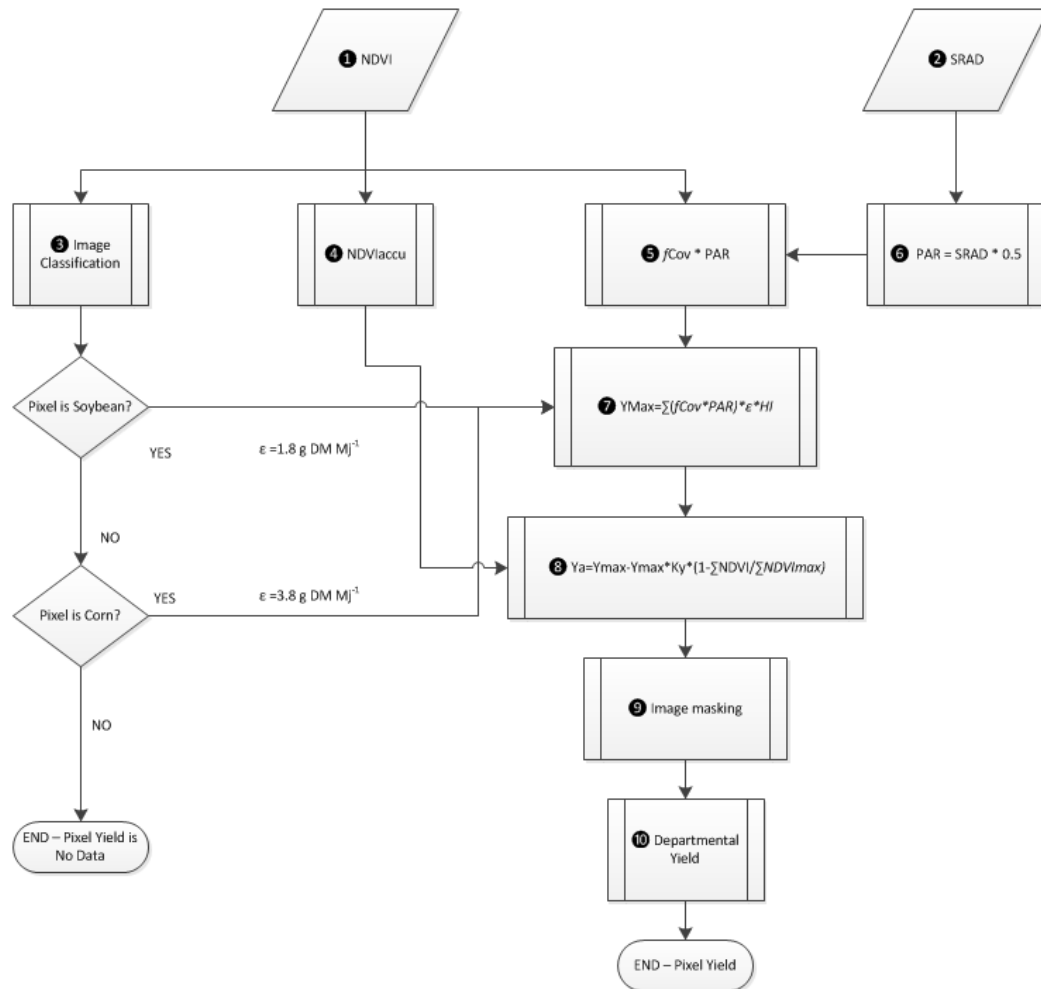


Figure 7.2 Flow chart of adopted methodology

7.5. Data processing and analysis

The various data processing steps, as indicated in figure 7.2 are further elaborated upon below.

7.5.1. NDVI images (step 1)

Once more display one of the 17 NDVI images, open the map list “sub_modis_ndvi” and display as example the first date image “sub_modis_ndvi_1” using as Representation “NDVI1”. Note that most of the necessary pre-processing has already been done, this mainly in order to limit the file size needed to conduct the exercise. Check the map values by pressing the left mouse button and roaming the mouse over the active map window. Note the time steps of each of the NDVI images as is given in table 7.1. Add to your active map window the polygon file “boundary”, use the display option “Boundaries Only”. From the Menu of your active Map Window, select “File => Open Pixel Information”. Check the content from the pixel information window; note that the departmental crop yield data have been added, identical to table 7.2. Move with the cursor over the northernmost Department, called San Justo and note the negative NDVI values over the water body. These negative NDVI values do not represent vegetation and therefore these will be reclassified as “no data” values”. Close all active map windows. Now from the

main ILWIS window, select the options “Operations => Raster Operations => MapList Calculation”. Fill the MapList Calculation window as given in figure 7.3 and press “Show” to execute the operation. Display the resulting maplist “sub_modis_ndvi_und” as an animated sequence and check the values, note that no data is represented by a “?”.

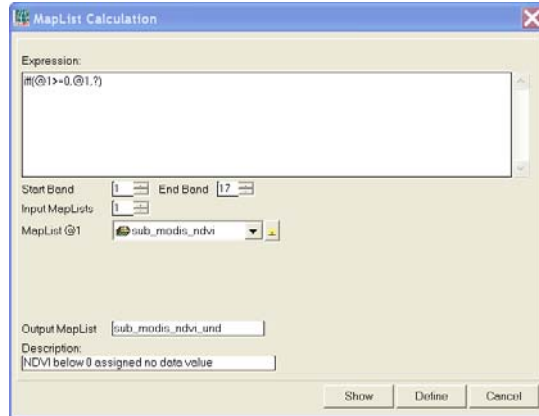


Figure 7.3 Reclassify negative NDVI values as no data values

7.5.2. Solar radiation (step 2)

The solar radiation values used are provided in table 7.1 (see column SRAD) and is further described under the section “Meteorological data” in chapter 7.3.3.

7.5.3. Crop classification (step 3)

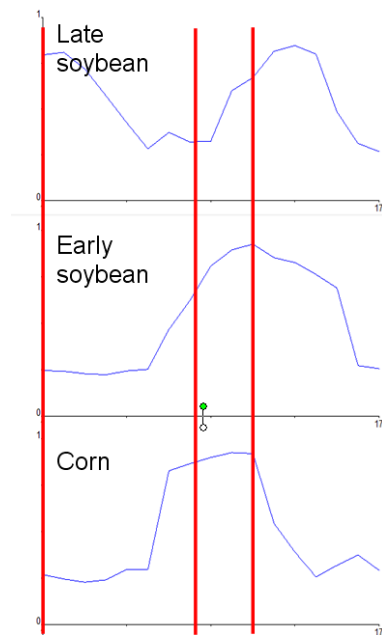


Figure 7.4 NDVI profiles

To evaluate different crops existence a multi criteria classification method was adopted based on the knowledge of corn and soybean growing cycles in Cordoba province as reflected by the NDVI profiles, see also figure 7.4. Soybean is cultivated in 2 different ways: late soybean (soybean_2) is sown after wheat so it is expected that the September NDVI values are high, they are lowest at harvest time in December, and rising to a maximum in February when soybean full cover occurs. Following this criteria a Boolean raster map can be calculated by typing the following expression in the command line of the main ILWIS menu:

```
soybean_2:=iff((sub_modis_ndvi_und_1>0.6)and(sub_modis_ndvi_und_7<0.3) and(sub_modis_ndvi_und_11>0.7),1,0)
```

Press enter to execute the operation and after the calculation has finished display the map. On the other hand, as early soybean (soybean_1) comes from fallow therefore the September NDVI is low, the sowing starts in November so the maximum NDVI appears in late December. To separate this crop we use the following expression:

```
soybean_1:=iff((sub_modis_ndvi_und_1<0.3)and(sub_modis_ndvi_und_8>0.7)and(sub_modis_ndvi_und_12>0.5)and(sub_modis_ndvi_und_15<0.3),1,0)
```

For corn, similar to early soybean, the minimum value occurs in September, but as thermal requirements are lower than soybean, the seeding can be earlier so it's maximum NDVI value is reached in November (corn_1) or December (corn_2). The expressions used for the classification of corn are:

```
corn_1:=iff((sub_modis_ndvi_und_1<0.3)and(sub_modis_ndvi_und_6>0.6)and(sub_modis_ndvi_und_15<0.3),1,0)
```

```
corn_2:=iff((sub_modis_ndvi_und_1<0.3)and(sub_modis_ndvi_und_7>0.7)and(sub_modis_ndvi_und_12<0.5)and(sub_modis_ndvi_und_15<0.3),1,0)
```

Execute the expressions from the command line of the main ILWIS menu, display and check your results. For the exercise we only need to know where soybean and corn are cropped because they have different radiation use efficiency values (ϵ), so we make a unique Boolean image for each crop using the following commands:

```
soybean:=iff((soybean_1=1)or(soybean_2=1),1,0)
corn:=iff((corn_1=1)or(corn_2=1),2,0)
```

To check the results of the classification, basically to see if crops are double classified, add the soybean and the corn maps together, using the following expression from the command line of the main ILWIS menu:

```
class_check:=corn+soybean
```

display the map using as Representation “lai_SAF” and visually check your results, note the values range from 0 to 3, as corn has been assigned a value of 2! Close the map and right click the mouse button over the map “class_check”, from the context sensitive menu, select the option “Statistics => Histogram” and press “Show” to see the statistics per class. To correct for the classification error, execute the following expression from the command line of the main ILWIS menu:

```
class_cor:=iff(class_check<3,class_check,0)
```

display the map using as Representation “lai_SAF” and visually check your results, note the values range now from 0 to 2, soybean is now classified with a value of 1 and corn has obtained a value of 2.

Finally the distribution of the classified pixels per department has to be considered. Right click the mouse button over the polygon map “boundary”, from the context sensitive menu, select the option “Polygon to Raster”, as Output Raster Map, leave “boundary”, use as Georeference “sub_modis_ndvi_1” and press “Show”. Note that the map is resampled to the NDVI georeference, which is in the original MODIS projection, the so-called Sinusoidal Projection, therefore the boundaries look distorted. Next step is to cross the raster map “boundary” with the map “class_cor”, select from the main ILWIS menu the option “Operations => Raster Operations => Cross” , as 1st Map specify “boundary” and as 2nd map select “class_cor”, as Output Table specify “representation_department” and press “Show”. Check the results shown in the displayed cross table, type the following expressions in the table command line:

```
pixel_soybean:=iff(class_cor=1,npix,?)
pixel_corn:=iff(class_cor=2,npix,?)
```

New columns are created showing the number of pixels representing corn and soybean per department. These two newly created columns are going to be added to the attribute table “boundary”. Close the table “representation_department” and open the table “boundary”. From the active table menu, select the option “Column => Join”, as table select “representation_department” and as Column “pixel_soybean”, press “Next” 4 times, accept the default Output Column “pixel_soybean” and press “Finish” and “OK”. Repeat this procedure to join also the “pixel_corn” column. Your results should represent those as provided in figure 7.5

	CornYield	SoybeanYield	pixel_soybean	pixel_corn
Calamuchita	7000	2442	1249	13
General Roca	6800	2300	1704	927
Gral San Martin	5500	2150	1900	745
Juarez Celman	6000	2370	2837	1432
Marcos Juarez	8000	3300	4584	766
Pte RS Pena	6500	2200	2592	788
Rio Cuarto	4000	2000	8075	2659
Rio Primero	6000	2200	4329	425
Rio Segundo	7000	2300	8152	491
San Justo	5500	2050	2378	151
Santa Maria	6500	2400	6647	198
Tercero Arriba	6500	2800	5531	621
Union	7000	2442	5537	1460
Min	4000	2000	1249	13
Max	8000	3300	8152	2659
Avg	6331	2381	4270	821
StD	978	343	2385	706
Sum	82300	30954	55515	10676

Figure 7.5 Yield and number of sample pixels per Department for corn and soybean

7.5.4. Sum of NDVI (step 4)

To calculate the sum of NDVI from all images during the crop cycle (from band 7 to 14) use the Maplist Statistics utility to obtain the `ndvi_sum`. From the main ILWIS window, select the options “Operations => Statistics => MapList => Maplist Statistics”. Fill the MapList Statistics window as given in figure 7.6 and press “Show” to execute the operation.

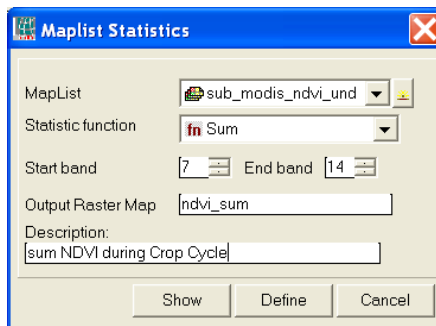


Figure 7.6 MapList Sum Function

Display the resulting “`ndvi_sum`” map using as Representation “`lai`” and note the minimum and maximum values of the map. Move the mouse with the left mouse cursor pressed over the active map window.

7.5.5. fCov*PAR calculation (steps 5 and 6)

For each of the NDVI maps during the crop cycle (from band 7 to 14), the `fCov` needs to be calculated, in this case using equation 7 (see chapter 7.3.4). This can be combined with the average of the solar radiation transformed to PAR ($PAR = SRAD * 0.5$) for a 16 days period (see table 7.1). Type the following expression in the command line of the main ILWIS menu:

$$fCov_PAR7 := (sub_modis_ndvi_und_7 * 1.228 - 0.245) * 10.25 * 16$$

use the default values and press “OK”. For first date, where the solar radiation was 20.5, the PAR is 10.25 $Mj\ m^{-2}\ d^{-1}$. Display the resulting map and check the values obtained, use as Representation “Pseudo”. Repeat this procedure for the other maps for the crop cycle using the expressions below (note the changing PAR values):

$$fCov_PAR8 := (sub_modis_ndvi_und_8 * 1.228 - 0.245) * 11.55 * 16$$


```

fCov_PAR9:=(sub_modis_ndvi_und_9*1.228-0.245)*11.65*16
fCov_PAR10:=(sub_modis_ndvi_und_10*1.228-0.245)*9.5*16
fCov_PAR11:=(sub_modis_ndvi_und_11*1.228-0.245)*9.8*16
fCov_PAR12:=(sub_modis_ndvi_und_12*1.228-0.245)*11.1*16
fCov_PAR13:=(sub_modis_ndvi_und_13*1.228-0.245)*9.1*16
fCov_PAR14:=(sub_modis_ndvi_und_14*1.228-0.245)*8.8*16

```

For all resulting fCov_PAR* maps a new MapList has to be created, from the main ILWIS menu, select “File => Create => MapList”, specify as Map list name “fCov_Par” and add the maps in a sequential order using the “>” sign. See also figure 7.7.

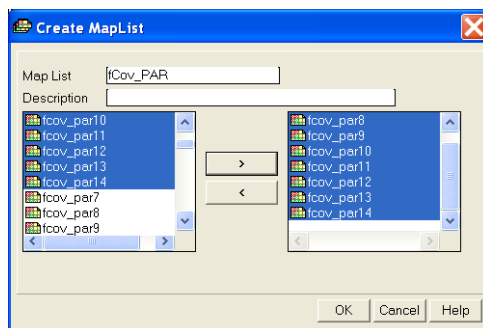


Figure 7.7 Final Maplist of fCov_PAR

7.5.6. Maximum yield – Ymax (step 7)

As shown in the flowchart (see figure 7.2), Ymax is calculated using the sum of fCov_PAR, multiplied by the Radiation Use Efficiency (ϵ) and the Harvest Index (HI). To calculate fCov_PAR_sum, use the Maplist Statistics option. From the main ILWIS menu, select the options “Operations => Statistics => MapList => Maplist Statistics”. Fill the MapList Statistics window as given in figure 7.8 and press “Show” to execute the operation.

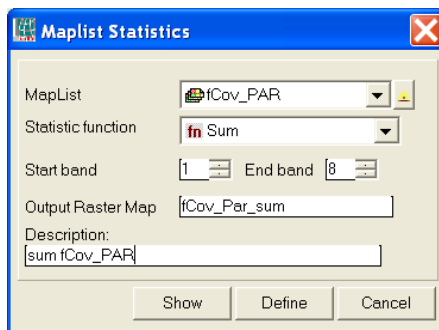


Figure 7.8 MapList Statistics SUM function of fCov_PAR

As there are negative values, this intermediate map is corrected and all negative values are re-assigned as undefined (?). Type the following expression on the command line in the main ILWIS menu:

```
fCov_PAR_sum_cor:=iff(fCov_Par_sum ge 0,fCov_Par_sum,?)
```

Use the settings as given in figure 7.9 for the “Raster Map Definition” and press “OK” to execute the operation.

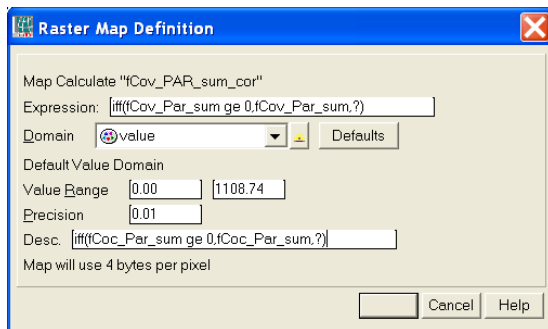


Figure 7.9 Raster Map Definitions

To estimate maximum yield (Ymax) for each crop one has to take into account different ϵ values (1.8 gr Mj-1 and 3.8 gr Mj-1 for soybean and corn, respectively (Sinclair and Mochow, 1999; Lindquist *et al.*, 2005). For both crops a harvest index (HI) of 0.47 is assumed. To obtain the estimated yield in kg ha-1 furthermore a conversion factor of 10 needs to be applied. These two computations can be done using a single expression from the command line in the main ILWIS menu:

```
Ymax_soybean:=iff(class_cor=1,fCov_Par_sum_cor*1.8*0.47*10,?)
```

```
Ymax_corn:=iff(class_cor=2,fCov_Par_sum_cor*3.8*0.47*10,?)
```

Execute both expressions and check the resulting maps.

7.5.7. Actual yield - Ya (Step ⑧)

From experimental data the accumulated NDVImax value obtained from of a set of 10 plots within the study area was 7.6 for the entire cycle. To account for different crop water stress sensibility a Ky value of 2.1 and 1.3 for soybean and corn is applied, respectively. The ILWIS commands to calculate the actual yield are shown below:

```
Ya_soybean:=iff(class_cor=1,Ymax_soybean-Ymax_soybean*2.1*(1-ndvi_sum/7.6),?)
```

```
Ya_corn:=iff(class_cor=2,Ymax_corn-Ymax_corn*1.3*(1-ndvi_sum/7.6),?)
```

Execute the expressions and display the resulting maps, check the values obtained.

7.5.8. Image Masking (step ⑨)

Display the map “Ya_soybean” and add to this map the polygon map “boundary” using the Display Options Info off and Boundaries Only. Repeat this procedure once more using the map “Ya_corn” and check the distribution of those pixels that have been used to calculate the yield of corn and soybean respectively. Also use the option “Pixel Information”, select “File => Pixel Information” from the active map display window. Close all active map windows.

7.5.9. Yield per Department (Step ⑩)

In order to obtain the average Yield per Department the yield of each crop of every agricultural administrative region has to be extracted and aggregated to obtain the average yield. To do so select from the main ILWIS in menu the options “Operations => Raster Operations => Cross”, as 1st Map select “boundary” and as 2nd map “Ya_corn”. As Output Table specify “department_corn” and press “Show” to execute the operation. Open the table “department_corn” and note the content of the table. From the table menu, select the option “Columns => Aggregation” and specify the Aggregate Column Options window as indicated in figure 7.10 (left) and press “OK”. Note that the average yield for corn is computed per department and the result is added to the table “boundary”, using a new column, named “Ya_corn”. Close the cross table.

Repeat the Cross operation, now using as 1st Map “boundary” and as 2nd map “Ya_soybean”. As Output Table specify “department_soybean” and press “Show” to execute the operation. Again note the content of the table created. Again use the aggregation function as given in figure 7.10 (right), now use the column “Ya_soybean”, as output table specify “boundary” and as output column “Ya_soybean”

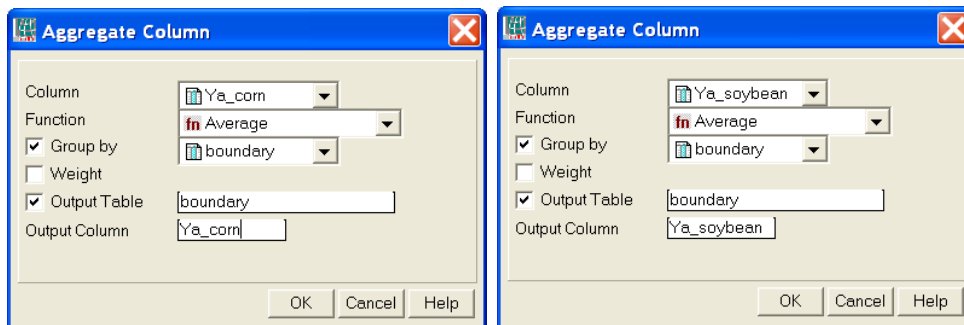


Figure 7.10 Table Aggregation of corn – soybean yield per Department

Now open the table “boundary” and inspect the newly created columns called “Ya_corn” and “Ya_soybean”. Also have a look at figure 7.11. From the table menu, select the options “Columns => Statistics”, select as function “Correlation” and calculate the correlation between the columns “CornYield” – “Ya_corn” and between the columns “SoybeanYield” – “Ya_soybean”.

	CornYield	SoybeanYield	pixel_soybean	pixel_corn	Ya_corn	Ya_soybean
Calamuchita	7000	2442	1249	13	4741.619	2773.733
General Roca	6800	2300	1704	927	5065.304	2195.645
Gral San Martin	5500	2150	1900	745	6491.594	2525.529
Juarez Celman	6000	2370	2837	1432	6255.835	2927.619
Marcos Juarez	8000	3300	4584	766	7097.131	3611.839
Pte RS Pena	6500	2200	2592	788	6258.860	2359.127
Rio Cuarto	4000	2000	8075	2659	5403.034	2948.936
Rio Primero	6000	2200	4329	425	7764.826	3025.973
Rio Segundo	7000	2300	8152	491	7000.258	3045.731
San Justo	5500	2050	2378	151	5836.679	2674.932
Santa Maria	6500	2400	6647	198	6984.910	3025.209
Tercero Arriba	6500	2800	5531	621	6151.758	2909.456
Union	7000	2442	5537	1460	6578.396	2905.232
Min	4000	2000	1249	13	4741.619	2195.645
Max	8000	3300	8152	2659	7764.826	3611.839
Avg	6331	2381	4270	821	6279.246	2840.689
StD	978	343	2385	706	858.636	355.027
Sum	82300	30954	55515	10676	81630.204	36928.960

Figure 7.11 Resulting table showing observed versus calculated yield

Calculate the residuals as well. Type from the table command line the following equations and press “OK” to execute these:

Res_corn:=cornyield-ya_corn

Res_soybean:=soybeanyield-ya_soybean

From the Table menu, select the “Graph” icon, in the “Create Graph” menu, unselect the “X-Axis” and select for the “Y-axis” the column “Res_corn” and press “OK”. From the left hand graph legend, double click the item “Res_corn” and change the representation to “Line”. From the Graph Menu, select “Edit => Add Graph => From Columns” and select the column “Res_soybean” and press “OK”. Again double click on the “Res_soybean” item in the graph legend and change it to a line representation, eventually change the colour. Double click on the graph title and change the name, repeat this also for the Y-Axis description. Your results should resemble those of figure 7.12.

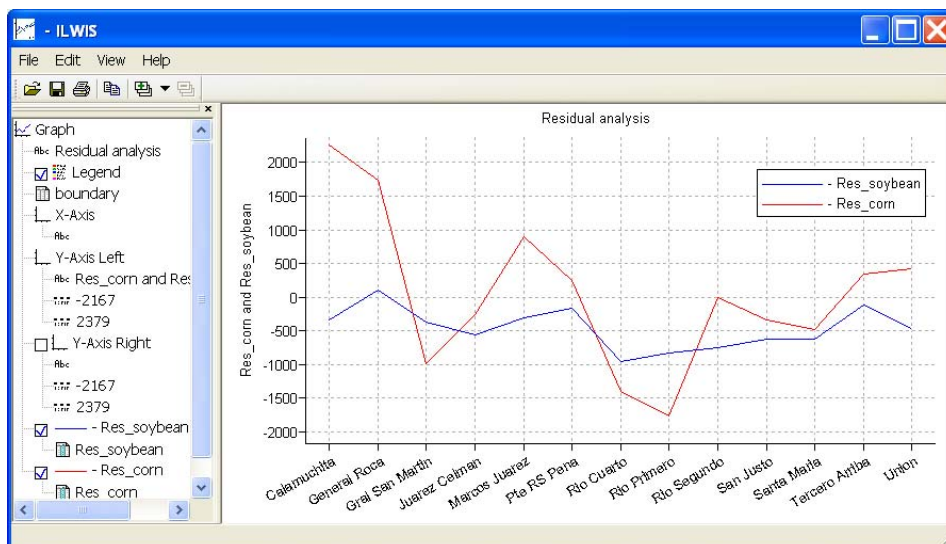


Figure 7.12 Residual analysis of the observed versus calculated yields

7.6. Conclusions

This exercise shows a methodology that was developed using a geographic information system for estimating corn and soybean yields for the province of Cordoba, Argentina, applying only NDVI data (derived from MODIS, having a pixel size of 250 m) and solar radiation as background information.

This procedure is a first prototype that, despite its simplified design, produces objective results which are in contrast with the qualitative survey method currently used by the state agency. It should be noted that in general far fewer pixels have been used to calculate the average yield for corn, for the Department Calamuchita only 13 pixels have been used. This might explain the high residual obtained but in general further validation of the approach is required. The FAO method for estimating crop productivity structured in a geographic information system is flexible to incorporate calculation routines in a modular format. According to the information available the estimation of Y_{max} , ET_{max} and η can be changed using methodologies which are more accurate but often more complex.

Improving the procedure at a later stage should take into account also the different sensitivity to water stress of crops at different phenological stages, as well as the use of spatially distributed rainfall data using satellite derived rainfall estimates.

Furthermore the MODIS derived NDVI could be replaced by the MSG (SEVIRI-Instrument) derived NDVI which is has currently become available.

REFERENCES

- Boote, K. J., J. W. Jones, and G. Hoogenboom (1998): Simulation of crop growth: CROPGRO Model. In: R. M. Peart and R. B. Curry (eds) *Agricultural Systems Modeling and Simulation*. Marcel Dekker, New York. Pp. 113-133.
- Brisson, N., C. Gary, E. Justes, R. Roche, B. Mary, D. Ripoche, D. Zimmer, J. Sierra, P. Bertuzzi, P. Burger, F. Bussi re, Y.M. Cabidoche, P. Cellier, P. Debaeke, J.P. Gaudill re, C. H nault, F. Maraux, B. Seguin, and H. Sinoquet (2003): An overview of the crop model STICS. *Europ. J. Agronomy* 18:309-332
- Caselles, V., E. Hurtado, y M.M. Artigao (1993): Determinaci n de la productividad de ma z mediante im genes NOAA-AVHRR. *Revista de Teledetecci n* 1:1-7
- de la Casa, A., y G. Ovando (2007): Integraci n del  ndice de Vegetaci n de la Diferencia Normalizada (NDVI) y del ciclo fenol gico de ma z para estimar el rendimiento a escala departamental en C rdoba, Argentina. *Agricultura T cnica (Chile)* 67(4):362-371.
- Doorenbos, J., and A.H. Kassam (1979): Yield response to water. FAO Irrigation and Drainage Paper No. 33. Rome, Italy.
- Doraiswamy, P.C., S. Moulin, P.W. Cook, and A. Stern (2003): Crop yield assessment from remote sensing. *Photogrammetric Engineering & Remote Sensing*, 69(6): 665-674.
- Edwards, J.T., L.C. Purcell, and E.D. Vories (2005): Light interception and yield potential of short-season maize (*Zea mays* L.) hybrids in the midsouth. *Agron. J.* 97:225-234.
- Funk, C., and M.E. Budde (2009): Phenologically-tuned MODIS NDVI-based production anomaly estimates for Zimbabwe. *Remote Sens. Environ.* 113:115-125.
- Gu erif M., and C.L. Duke (2000): Adjustment procedures of a crop model to the site specific characteristics of soil and crop using remote sensing data assimilation. *Agricultural Ecosystems & Environment* 81:57-69.
- Lindquist, J.L., T.J. Arkebauer, D.T. Walters, K.G. Cassman, and A. Dobermann (2005): Maize radiation use efficiency under optimal growth conditions. *Agron. J.*, 97:72-78.
- Moriondo, M., F. Maselli, and M. Bindi (2007): A simple model of regional wheat yield based on NDVI data. *Europ. J. Agronomy* 26: 266-274
- Purcell, L.C. (2000): Soybean canopy coverage and light interception measurements using digital imagery. *Crop Science* 40:834-837.
- Raes, D., S. Geerts, E. Kipkorir, J. Wellens, and A. Sahli (2006): Simulation of yield decline as a result of water stress with a robust soil water balance model. *Agricultural Water Management* 81:335-357.
- Rizzi R., e B.F.T. Rudorff (2005): Estimativa da produtividade de soja por meio de um modelo agrometeorol gico-espectral: estudo de caso no Rio Grande do Sul. Anais XII Simp sio Brasileiro de Sensoriamento Remoto, Goi nia, Brasil, 16-21 abril 2005, INPE, p. 237-244.
- Rojas, O. (2007): Operational maize yield model development and validation based on remote sensing and agrometeorological data in Kenya. *International Journal of Remote Sensing* 28:3775-3793.

Rosenthal W.D., Hammer G.L., and D. Butler (1998): Predicting regional grain sorghum production in Australia using spatial data and crop simulation modeling. *Agric. For. Meteorol.* 91:263-274.

SAyGA (2010): Secretaría de Agricultura, Ganadería y Alimentos de la Provincia de Córdoba. Estadísticas de producción agrícola. <http://www.cba.gov.ar>

Sinclair, T.R., and R.C. Muchow (1999): Radiation use efficiency. *Adv. Agron.* 65:216-265.

Yang, H.S., A. Dobermann, J.L. Lindquist, D.T. Walters, T.J. Arkebauer, and K.G. Cassman (2004): Hybrid-maize: A maize simulation model that combines two crop modeling approaches. *Field Crops Research* 87:131-154.