Crop Monitoring as an
E-agricultural tool in
Developing Countries

ASSESSMENT REPORT ON THE MULTI-MODEL APPROACH FOR WHEAT MONITORING AND YIELD FORECASTING IN MOROCCO

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Author(s):Valentina Pagani, Davide Fumagalli, Fabien Ramos, Riad Balaghi, Samira Ismaili, Tarik El Hairech, Caterina Francone, Roberto Confalonieri
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DOCUMENT CONTROL

Signatures

Author(s) : Valentina Pagani
Davide Fumagalli
Fabien Ramos
Riad Balaghi
Samira Ismaili
Tarik El Hairech
Caterina Francone
Roberto Confalonieri

Reviewer(s) :

Approver(s) :

Issuing authority :

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EXECUTIVE SUMMARY

The multi-model approach to crop monitoring and yield forecasting was here tested using the BioMA models CropSyst and WOFOST for soft and durum wheat in Morocco. Parameterizations derive from the activities carried out within E-AGRI WP3 tasks, reported in deliverables D31.1, D31.2, D34.1, D34.2, D34.3, D34.4, and D35.1.

Within this task, we tested the multi-model approach

(i) for different species (durum and soft wheat),

(ii) for different regions,

(iii) for performing yield forecasting in different moments during the crop cycle (maturity decade or one month before maturity).

This design allowed demonstrating that the different approaches implemented in different crop models to formalize biophysical processes involved with crop growth and development could make a model more suitable than others under certain conditions (regions, species).

Results, indeed, showed that WOFOST achieved the highest reliability for both durum and soft wheat forecasts when the forecasting event was triggered at maturity on the whole Morocco; on the contrary, for forecast events triggered one month before maturity, CropSyst resulted the most accurate in case of soft wheat. At national level, R^2 between historical official statistics and forecasted yields ranged between 0.61 and 0.83.

For durum wheat, at regional level, WOFOST achieved the best performance metrics in four out of seven regions for all the combinations species × forecasting moment, although the regions changed across combinations. For soft wheat, CropSyst resulted the most suitable in five out of seven regions at maturity, and in four out of seven regions one month before.

These results confirm the usefulness and the potentialities of the multi-model approach to in season, large area wheat monitoring and yield forecasting.

1. Introduction

As discussed in the E-AGRI deliverable D33.2, the international scientific community is increasingly moving towards multi-model approaches for crop yield predictions. However, in most of the cases, this is done by running different models and deriving statistics from their outputs (e.g., the median), like in the activities carried out within the AgMIP (The Agricultural Model Inter-comparison and Improvement Project; http://www.agmip.org/) network (Asseng et al., 2013).

We evaluated here a different approach to multi-model simulations, based on the idea that the specific formalization of biophysical processes within a specific model could lead to the highest reliability under specific conditions. This idea, partly deviating from the AgMIP approach, allowed achieving good results when applied – within the E-AGRI activities – to rice monitoring and yield forecasts in Jiangsu.

2. Materials and methods

2.1. Modelling solutions

The BioMA models used in this study – CropSyst (Stöckle et al., 2003) and WOFOST (Van Keulen and Wolf, 1986) – have been already presented and described in previous E-AGRI reports (e.g., D34.3). For all of them, modelling solutions including disease simulation were developed, using the approach proposed by Bregaglio et al. (2013). Since the complete solutions require specific hourly weather data, weather generators were coupled to the modelling solutions. In particular, the following software components implementing weather data generators were used:

- CRA.Clima.Wind for wind speed generation (Donatelli et al., 2009; http://agsys.cra-cin.it/tools/wind/help/);
- CRA.Clima.AirT for hourly air temperature data (Donatelli et al., 2010; http://agsys.cra-cin.it/tools/airtemperature/help/);
- CRA.Clima.Evapotranspiration for hourly air relative humidity data (Bregaglio et al., 2010; http://agsys.cra-cin.it/tools/evapotranspiration/help/);
- JRC.IPSC.MARS.Diseases.LeafWetness for leaf wetness data (Bregaglio et al., 2011; http://agsys.cra-cin.it/tools/leafwetness/help/).

Hourly weather data are generated at runtime, thus without needing extension of the database, as compared to what is normally used by CGMS-type applications.

2.2. Simulation experiments

2.2.1. Data and parameterizations

Soft and durum wheat crops were simulated on each of the elementary simulation units corresponding to the cells of the 25 km × 25 km grid of the MARS database.

Parameterizations for the crop models derive from the calibration and validation activities detailed in E-AGRI report D34.3. Parameters for the “UNIMI.Disease” model where derived from literature, since they are related to pathogen characteristics with a clear biological meaning and high quality measurements are available from experiments carried out in controlled environment. Aggregation of simulated data at regional and national levels (based on percentage crop cover in simulation units) was performed using the same crop mask used to identify the elementary simulation units.

2.2.2. Testing the multi-model approach

In order to test the multi-model approach to wheat monitoring, the following factors were considered:

- moment when the forecasting event is triggered;
- climate conditions explored.

Concerning the forecasting moment, it was triggered twice: (i) when all the crops simulated in all the elementary units have reached the physiological maturity stage and (ii) three decades before. This test allowed analyzing possible differences in the monitoring capability of the BioMA models while the crops are approaching the harvest period.

Possible differences in the BioMA models suitability according to the climate conditions explored were instead evaluated by performing yield forecasts for different regions within the Moroccan cropped area. It should be noticed that these regions do not correspond to homogeneous agro-climatic zones; hence, there could be a variability in relative model responses even within regions.

All these activities were performed separately for durum and soft wheat (low potential varieties).

The resulting tests performed with the two BioMA models are summarized in Table 1, and led to 64 forecasting experiments (items in Table 1 × two models × two groups of cultivars), each made of 14-year simulations on 333 elementary simulation units.

Since CropSyst does not implement approaches for the dynamic partitioning of assimilates, indicators involved with storage organs biomass were not used in this study: this allowed testing the multi-model approach in a coherent way.

Table 1 Factors considered during the study.

Test ID	Monitoring time[a]	Regions
1	M	Morocco
2	M	Centre
3	M	Centre Nord
4	M	Centre Sud
5	M	Nord Ouest
6	M	Oriental
7	M	Sud
8	M	Tensift
9	3BM	Morocco
10	3BM	Centre
11	3BM	Centre Nord
12	3BM	Centre Sud
13	3BM	Nord Ouest
14	3BM	Oriental
15	3BM	Sud
16	3BM	Tensift

[a]: M: Physiological maturity reached in all simulation units; 3BM: three decades before physiological maturity is reached.

Simulation results were post-processed, together with historical series of statistical data, to produce the forecasts using the MARS CGMS Statistical Toolbox application integrated in the BioMA environment. Forecasts reliability for each of the combination crop model × monitoring time × climate condition were evaluated by means of indices of agreement between official and forecasted yields resulting from a cross-validation (leave-one-out): R^2 (coefficient of determination of the linear regression) and RRMSE (relative root mean square error, expressed as percentage).

3. Results and discussion

Results are presented in the following sections:

3.1.1. refers to durum wheat forecasts triggered when the crop has reached the physiological maturity stage in all the elementary simulation units;

3.1.2. refers to durum wheat forecasts triggered three decades before maturity;

3.2.1. refers to soft wheat forecasts triggered at physiological maturity;

3.2.2. refers to soft wheat forecasts triggered three decades before maturity.

For each section, the differences due to BioMA models used are discussed.

3.1. Durum wheat

3.1.1. Forecast event triggered at physiological maturity

Results of the multi-model approach to durum wheat monitoring at maturity are shown in Tables 2 and 3, and in Figures from 1 to 8.

The accuracy of the forecasts is satisfactory, with most of the RRMSE values around 20% (Table 2). WOFOST achieved the best values for both the agreement metrics in five out of eight cases, including the forecast performed at national level; CropSyst prevailed in the others.

At regional level, the best performances were achieved in the regions Centre (R^2 = 0.83; WOFOST), Oriental (R^2 = 0.84; WOFOST) and Tensift (R^2 = 0.89; CropSyst), whereas both the models presented the highest degree of uncertainty in Centre Nord (R^2 = 0.57 and 0.47 for WOFOST and CropSyst, respectively).

Table 2 Multi-model durum wheat monitoring in Morocco; results of the cross validation for the forecast event triggered at maturity. Bold-red indicates the best value for the metric.

Region	Trend	WOFOST	CropSyst
	R^2		
Morocco	Linear	**0.83**	0.75
Centre	No trend	**0.83**	0.67
Centre Nord	No trend	**0.57**	0.47
Centre Sud	No trend	0.64	**0.68**

Nord Ouest	No trend	0.53	**0.74**
Oriental	No trend	**0.84**	0.71
Sud	Linear	**0.76**	0.67
Tensift	Linear	0.67	**0.89**
	RRMSE (%)		
Morocco	Linear	**16.61**	20.10
Centre	No trend	**18.51**	25.57
Centre Nord	No trend	**31.68**	35.43
Centre Sud	No trend	24.69	**23.35**
Nord Ouest	No trend	16.54	**12.23**
Oriental	No trend	**23.68**	31.89
Sud	Linear	**26.54**	31.20
Tensift	Linear	33.04	**19.08**

Figures from 1 to 8 show the agreement between official and forecasted yields.
At national level (Figure 1), WOFOST over- and underestimated the yields recorded in 2007 (dry season) and 2009 (very wet season), respectively, whereas it presented a high accuracy in all the remaining years. CropSyst underestimated official yields in 2004 and 2006 (wet seasons), whereas a slight overestimation was observed for 2010 (slightly above average season).
Similar performances of the two models were observed for the Centre region (Figure 2), with one over- and one underestimation for WOFOST (2007 and 2001) and two yields underestimated by CropSyst (2004 and 2009), that also presented a marked overestimation in 2010. The amount of inter-annual variability explained by CropSyst – in this region – was 16% lower than the one explained by WOFOST.
Both the models presented a high degree of uncertainty in Centre Nord region (Figure 3), where under- and overestimations were achieved for many of the years in the historical series, although – even in this case – WOFOST presented the best performances.
The situation depicted for Centre Sud and Nord Ouest regions is decidedly better, with CropSyst resulting the most accurate, with just slight underestimation problems in the second part of the series (Figures 4 and 5).
Results achieved for Oriental and Sud regions presented an opposite behavior, with WOFSOT presenting good performances, without relevant under- or overestimations

(Figures 6 and 7). In Sud region, both the models presented the highest uncertainty in the first part of the season.

In Tensift region (Figure 8), CropSyst obtained the best performances for this series of forecasts (durum wheat at maturity): with the exception of 2008 (dry season), where a slight overestimation was observed, the model reproduced the inter-annual yield variability in the region with high precision. On the contrary, WOFOST failed to forecast yields in 2004, 2006 and 2009 (wet seasons).

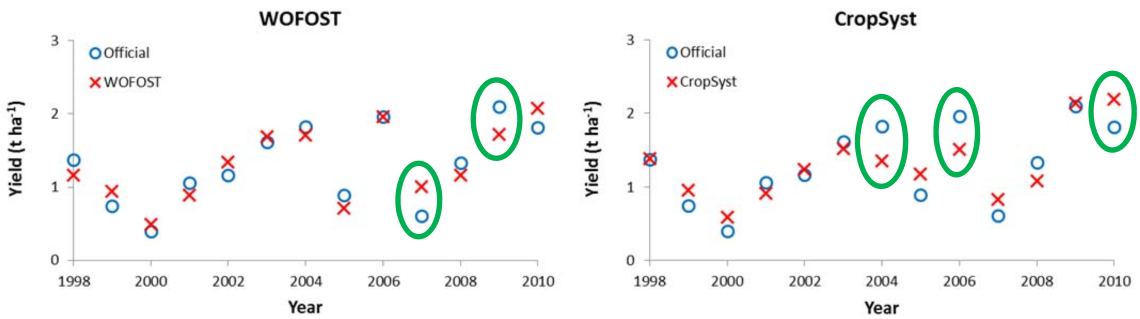

Figure 1 Multi-model durum wheat monitoring in Morocco; decade: maturity.

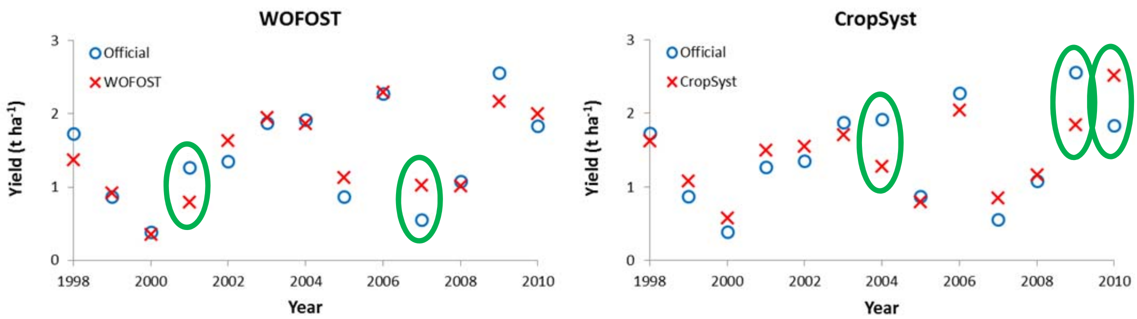

Figure 2 Multi-model durum wheat monitoring in Centre region; decade: maturity.

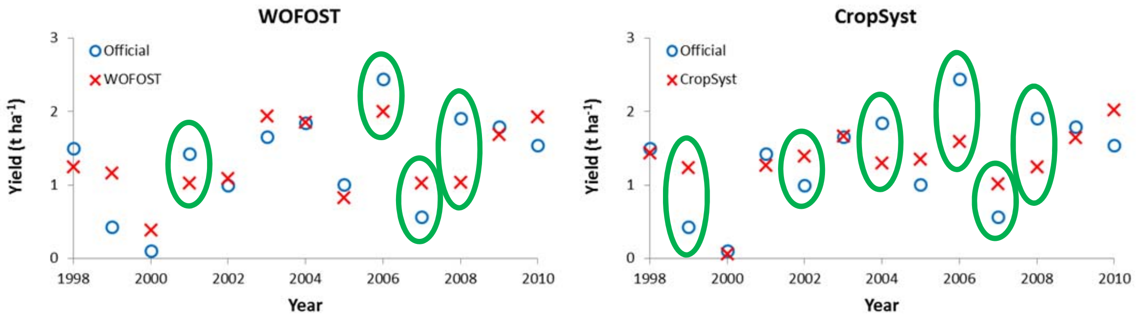

Figure 3 Multi-model durum wheat monitoring in Centre Nord region; decade: maturity.

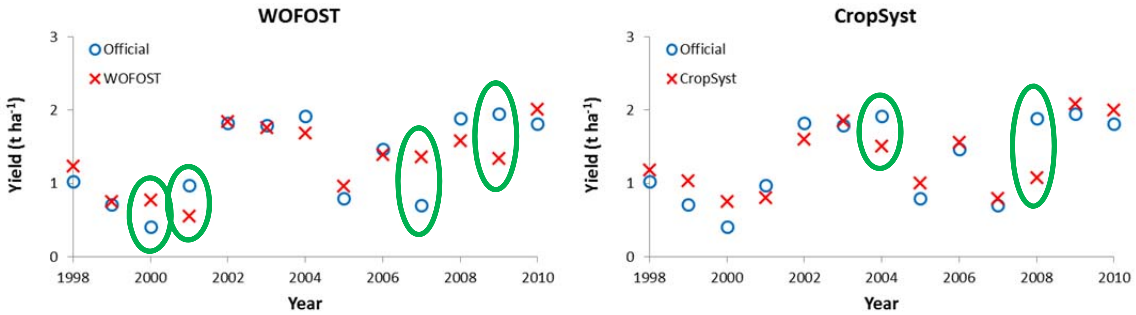

Figure 4 Multi-model durum wheat monitoring in Centre Sud region; decade: maturity.

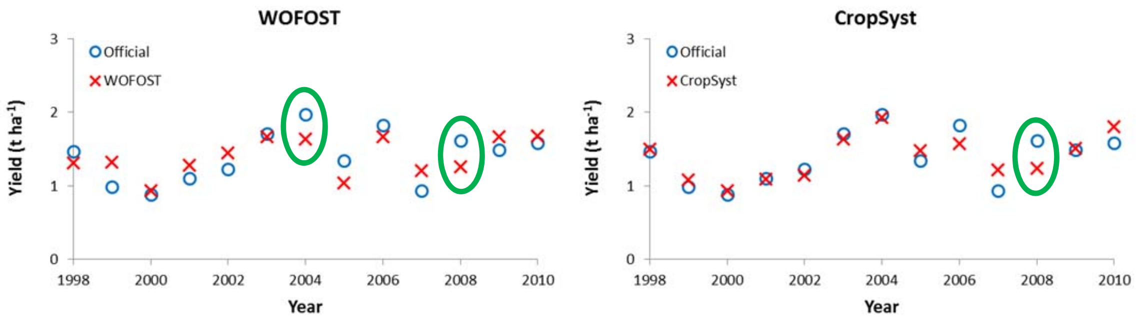

Figure 5 Multi-model durum wheat monitoring in Nord Ouest region; decade: maturity.

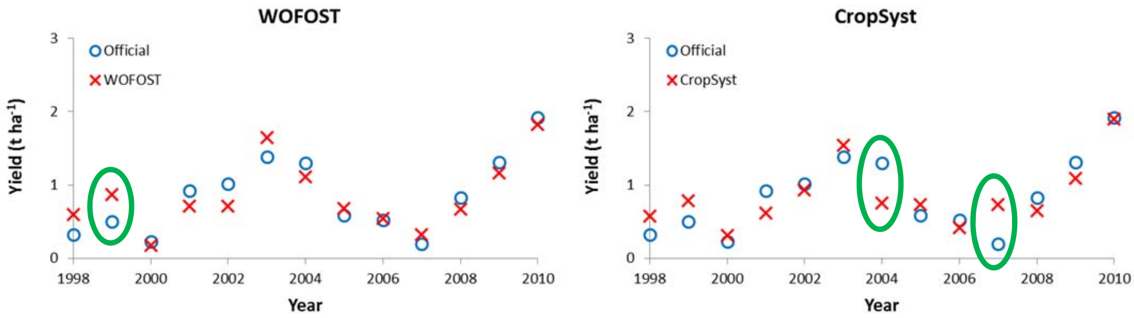

Figure 6 Multi-model durum wheat monitoring in Oriental region; decade: maturity.

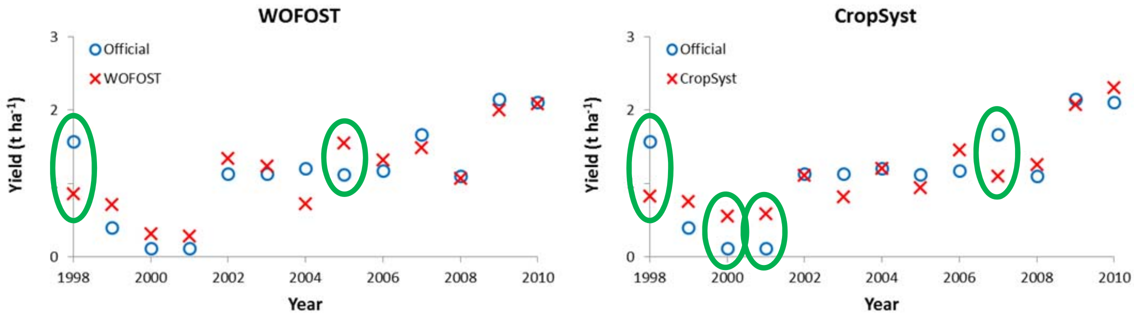

Figure 7 Multi-model durum wheat monitoring in Sud region; decade: maturity.

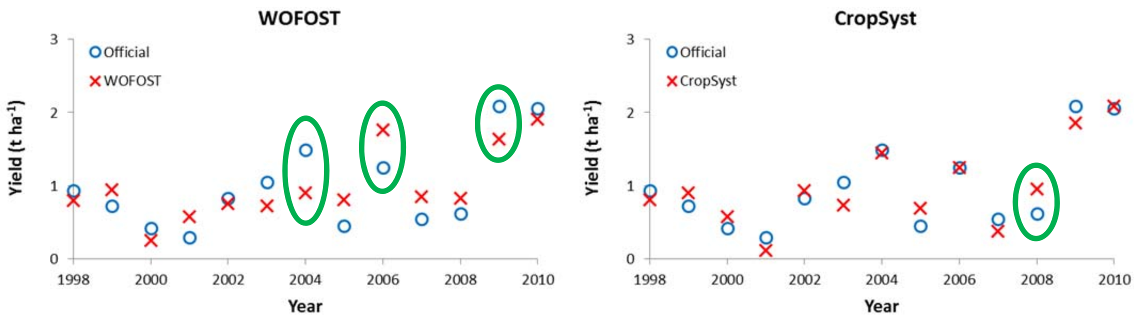

Figure 8 Multi-model durum wheat monitoring in Tensif region; decade: maturity.

Table 3 presents – for each region and model – the indicators selected by the stepwise regression procedure performed by the CGMS Statistical Toolbox. Indicators involved with the simulation of plant-pathogen interactions resulted important to explain the inter-annual variability in official yields in 11 out of 16 cases.

It is interesting to notice that the number of infection events (indicator #7, "n. infections") – that is the only indicator not representing a state variable of the model – was often selected.

Table 3 Indicators selected by the stepwise regression performed between official yields and aggregated simulation outputs; forecast event triggered when maturity is reached in all the elementary simulation units.

WOFOST	CropSyst
Morocco	
3 (LAGB)[a]	1 (PAGB)[b]
7 (n. infections)[c]	5 (PDVS)[d]
8 (PLAI)[e]	7 (n. infections)
9 (LLAI)[f]	9 (LLAI)
Centre	
1 (PAGB)	1 (PAGB)
3 (LAGB)	3 (LAGB)
5 (PDVS)	7 (n. infections)
7 (n. infections)	9 (LLAI)
Centre Nord	
1 (PAGB)	1 (PAGB)
3 (LAGB)	3 (LAGB)
7 (n. infections)	7 (n. infections)
8 (PLAI)	9 (LLAI)
Centre Sud	
1 (PAGB)	1 (PAGB)
3 (LAGB)	3 (LAGB)
8 (PLAI)	8 (PLAI)
9 (LLAI)	9 (LLAI)
Nord Ouest	
3 (LAGB)	1 (PAGB)

7 (n. infections)	3 (LAGB)
8 (PLAI)	5 (PDVS)
9 (LLAI)	7 (n. infections)
Oriental	
1 (PAGB)	1 (PAGB)
5 (PDVS)	3 (LAGB)
7 (n. infections)	5 (PDVS)
9 (LLAI)	9 (LLAI)
Sud	
1 (PAGB)	1 (PAGB)
3 (LAGB)	3 (LAGB)
5 (PDVS)	5 (PDVS)
8 (PLAI)	7 (n. infections)
Tensift	
1 (PAGB)	3 (LAGB)
3 (LAGB)	5 (PDVS)
5 (PDVS)	8 (PLAI)
7 (n. infections)	9 (LLAI)

[a]: limited aboveground biomass
[b]: potential aboveground biomass
[c]: number of infection events
[d]: potential development stage code
[e]: potential leaf area index
[f]: limited leaf area index

3.1.2. Forecast event triggered three decades before maturity

Results of the multi-model approach to durum wheat monitoring three decades before maturity are shown in Tables 4 and 5, and in Figures from 9 to 16.

Contrarily to what expected, the average reliability of the forecasts (mean RRMSE = 24.66%) is very close to the one achieved at the late stage (mean RRMSE = 24.39%, see section 3.1.1), although forecasted yields at national level are now slightly less accurate (Table 4): RRMSE is now 21.41% and 22.00% for WOFOST and CropSyst, respectively, compared to 16.61% and 20.10% achieved when the forecast event was triggered at maturity. Moreover, accuracy is now more spread, with coefficient of variation of RRMSE 3% higher and RRMSE values ranging from 9.90% to 34.78%.

WOFOST obtained the best values for both the evaluation metrics in four regions out of seven, although the best performances were achieved by CropSyst in Centre and Tensift regions, with R^2 equal to 0.82 and 0.97, respectively; the accuracy shown for Tensift is decidedly satisfactory.

Table 4 Multi-model durum wheat monitoring in Morocco; results of the cross validation for the forecast event triggered three decades before maturity. Bold-red indicates the best value for the metric.

Region	Trend	WOFOST	CropSyst
		R^2	
Morocco	Linear	**0.72**	0.70
Centre	No trend	0.68	**0.82**
Centre Nord	No trend	**0.53**	0.49
Centre Sud	No trend	**0.58**	0.51
Nord Ouest	No trend	**0.51**	0.51
Oriental	No trend	**0.76**	0.68
Sud	Linear	0.65	**0.67**
Tensift	Linear	0.94	**0.97**
		RRMSE (%)	
Morocco	Linear	**21.41**	22.00
Centre	No trend	25.17	**18.71**

Centre Nord	No trend	**33.21**	34.78
Centre Sud	No trend	**26.74**	28.89
Nord Ouest	No trend	**16.84**	16.97
Oriental	No trend	**28.60**	33.39
Sud	Linear	31.99	**31.25**
Tensift	Linear	14.68	**9.90**

Figures from 9 to 16 show the agreement between official and forecasted yields.

At national level (Figure 9), the behavior of the two models was very similar, with overall good performances in the first part of the historical series counterbalanced by marked underestimations in 2004 and 2006 and overestimations in 2007 and 2010.

A similar behavior was observed for the Centre region (Figure 10), with the models demonstrating a good forecasting capability in most of the years and uncertainty in 1999 and 2010 (overestimation), and in 2009 (underestimation). Moreover, WOFOST presented relevant uncertainties also in 1998 and 2007.

Figure 11 confirms the difficulties encountered by both the modelling approaches in Centre Nord region already shown in Table 4. In this case – indeed – the errors are distributed in most of the years, revealing that a source of uncertainty (e.g., in the characterization of varieties or in the definition management practices) is not properly accounted for by the simulation system.

On the contrary, Figures 12, 14 and 15 shows that both the models present problems only in a specific part of the historical series: the second for Centre Sud region, and the first for the Oriental and Sud ones. This leads to hypothesize that the setup of the monitoring system is generally fine, and that specific discontinuity factors should be further investigated (e.g., shift to new genotypes or changes in the technology used).

The situation improves when moving in the Nord Ouest and Tensift regions (Figures 13 and 16), where both the modelling approaches demonstrated a satisfactory forecasting capability, especially in Tensift.

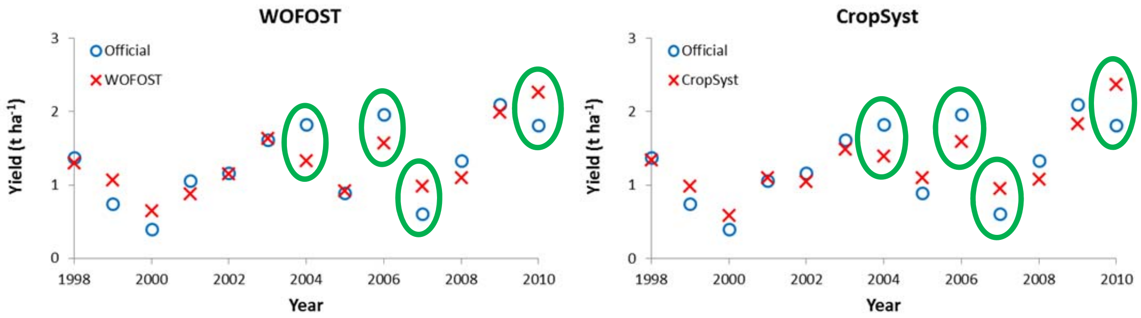

Figure 9 Multi-model durum wheat monitoring in Morocco; decade: 3 before maturity.

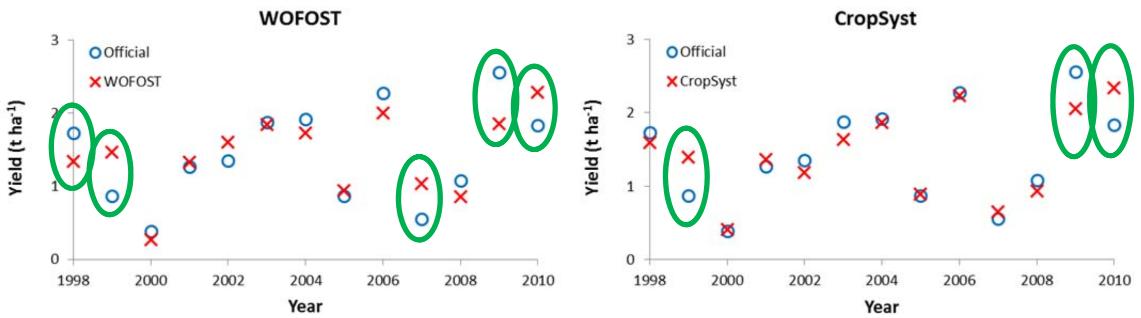

Figure 10 Multi-model durum wheat monitoring in Centre region; decade: 3 before maturity.

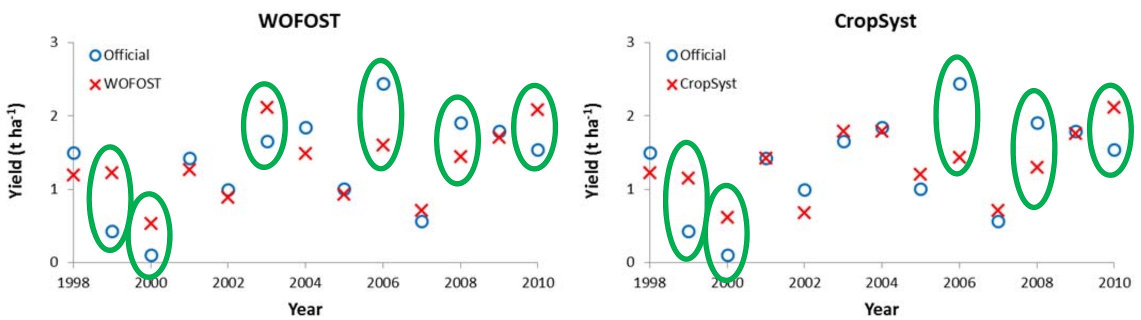

Figure 11 Multi-model durum wheat monitoring in Centre Nord region; decade: 3 before maturity.

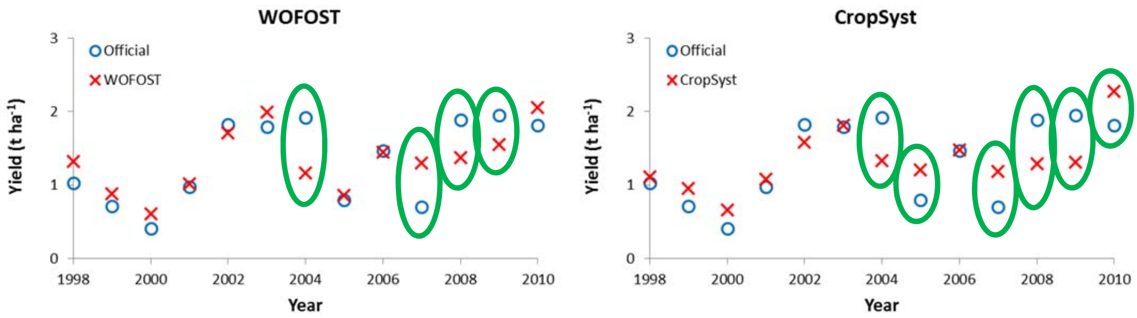

Figure 12 Multi-model durum wheat monitoring in Centre Sud region; decade: 3 before maturity.

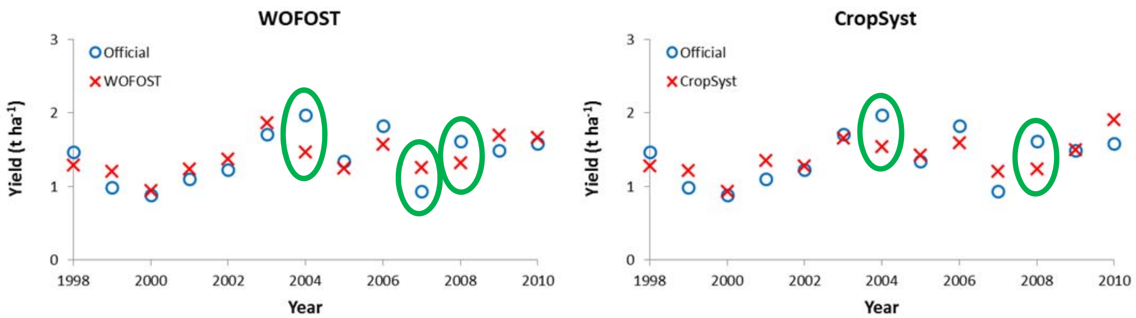

Figure 13 Multi-model durum wheat monitoring in Nord Ouest region; decade: 3 before maturity.

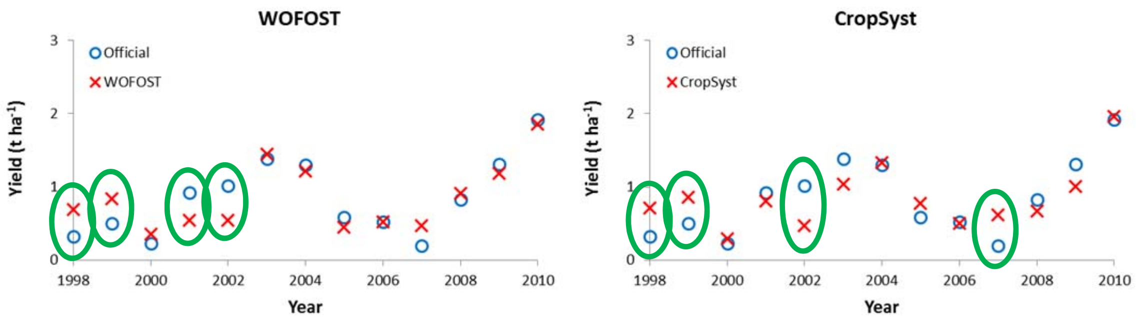

Figure 14 Multi-model durum wheat monitoring in Oriental region; decade: 3 before maturity.

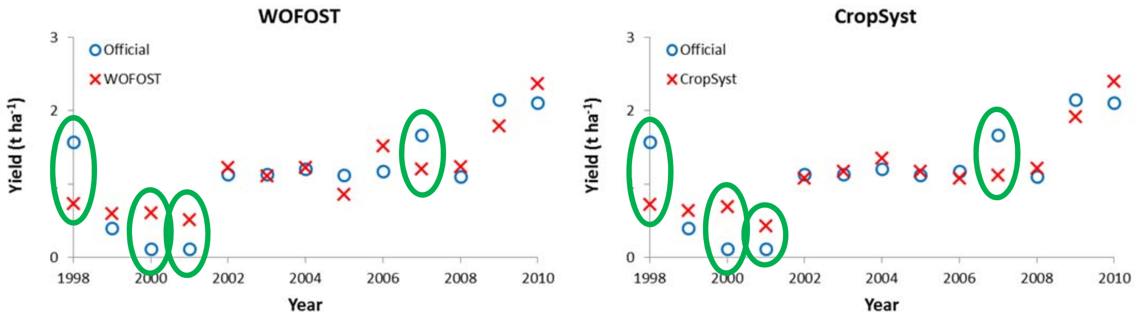

Figure 15 Multi-model durum wheat monitoring in Sud region; decade: 3 before maturity.

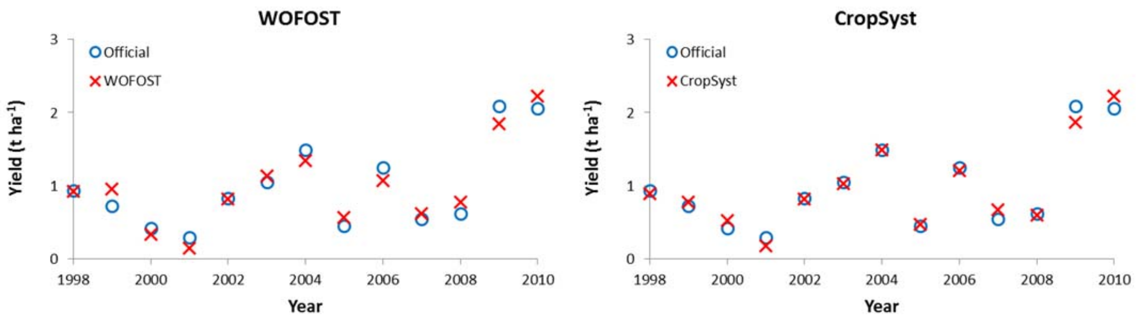

Figure 16 Multi-model durum wheat monitoring in Tensift region; decade: 3 before maturity.

Table 5 presents – for each region and model – the indicators selected by the stepwise regression procedure performed by the CGMS Statistical Toolbox.

The number of infection events (indicator #7, "n. infections") was selected in 10 out of 16 cases, confirming the importance of the simulation of the interaction between plant and pathogens.

The frequent (nine out of 16 cases) selection of development stage code (indicator #5, "PDVS") demonstrates the importance of thermal fluctuations in determining the year-to-year variability in yields, although rainfall are surely the main driver for wheat production in the Country.

Table 5 Indicators selected by the stepwise regression performed between official yields and aggregated simulation outputs; forecast event triggered three decades before maturity.

WOFOST	CropSyst
Morocco	
3 (LAGB)[a]	1 (PAGB)[b]
5 (PDVS)[c]	3 (LAGB)
7 (n. infections)[d]	7 (n. infections)
8 (PLAI)[e]	9 (LLAI)[f]
Centre	
3 (LAGB)	1 (PAGB)
5 (PDVS)	5 (PDVS)
7 (n. infections)	7 (n. infections)
9 (LLAI)	9 (LLAI)
Centre Nord	
3 (LAGB)	3 (LAGB)
7 (n. infections)	5 (PDVS)
8 (PLAI)	8 (PLAI)
9 (LLAI)	9 (LLAI)
Centre Sud	
3 (LAGB)	1 (PAGB)
5 (PDVS)	3 (LAGB)
7 (n. infections)	5 (PDVS)
8 (PLAI)	9 (LLAI)
Nord Ouest	
1 (PAGB)	1 (PAGB)
3 (LAGB)	3 (LAGB)
8 (PLAI)	7 (n. infections)
9 (LLAI)	9 (LLAI)

Oriental	
3 (LAGB)	3 (LAGB)
5 (PDVS)	5 (PDVS)
7 (n. infections)	7 (n. infections)
8 (PLAI)	8 (PLAI)
Sud	
3 (LAGB)	1 (PAGB)
7 (n. infections)	3 (LAGB)
8 (PLAI)	8 (PLAI)
9 (LLAI)	9 (LLAI)
Tensift	
1 (PAGB)	1 (PAGB)
3 (LAGB)	3 (LAGB)
8 (PLAI)	5 (PDVS)
9 (LLAI)	8 (PLAI)

[a]: limited aboveground biomass
[b]: potential aboveground biomass
[c]: potential development stage code
[d]: number of infection events
[e]: potential leaf area index
[f]: limited leaf area index

3.2. Soft wheat

3.2.1. Forecast event triggered three decades before maturity

Results of the multi-model approach to durum wheat monitoring at maturity are shown in Tables 6 and 7, and in Figures from 17 to 24.

In general, results for soft wheat (Table 6) are characterized by a higher degree of uncertainty compared to those obtained for durum wheat (see section 3.1.1).

Although WOFOST performances were slightly better at national level (RRMSE = 18.24% compared to 19.38%), CropSyst achieved the best values for both the metrics in five regions out of seven, demonstrating a satisfying reliability especially in the southern and eastern areas.

Results are characterized by a relevant heterogeneity, with R^2 ranging from 0.35 (WOFOST, Centre Nord and Centre Sud regions) to 0.88 (CropSyst, Oriental region).

Table 6 Multi-model soft wheat monitoring in Morocco; results of the cross validation for the forecast event triggered at maturity. Bold-red indicates the best value for the metric.

Region	Trend	WOFOST	CropSyst
	R^2		
Morocco	Linear	**0.74**	0.71
Centre	No trend	**0.52**	0.51
Centre Nord	No trend	0.35	**0.48**
Centre Sud	No trend	0.35	**0.65**
Nord Ouest	No trend	0.43	**0.54**
Oriental	No trend	0.64	**0.88**
Sud	Linear	**0.82**	0.77
Tensif	Linear	0.67	**0.77**
	RRMSE (%)		
Morocco	Linear	**18.24**	19.38
Centre	No trend	**26.76**	27.22
Centre Nord	No trend	41.24	**36.71**
Centre Sud	No trend	32.95	**24.03**

Nord Ouest	No trend	22.59	**20.42**
Oriental	No trend	30.57	**17.82**
Sud	Linear	**16.42**	18.81
Tensift	Linear	35.77	**29.68**

Figures from 17 to 24 show the agreement between official and forecasted yields.
At national level (Figure 17), both the models presented a satisfactory reliability, without relevant under- or overestimations (with few exceptions), although a slight – although diffuse – uncertainty characterizes the results throughout the whole historical series.
On the contrary, poor results were observed for both models in the Centre Nord and Centre Sud regions (Figures 19 and 20), where the monitoring system cannot be considered ready for an operational use.
CropSyst showed to be able to reproduce the inter-annual trend in official yields in Nord Ouest region, where WOFOST demonstrated a poor reliability (Figure 21). The opposite was observed in the Centre region (Figure 18), where only WOFOST correctly reproduced the yields in most of the years, although important errors were observed in 2007 (dry season, overestimation) and 2009 (very wet season, underestimation).
Both the models presented a satisfying behavior in Oriental (Figure 22), Tensift (Figure 24) and Sud (Figure 23) regions (arid zones). With few exceptions, they can be considered ready for an operational use in these regions, especially CropSyst, which correctly reproduced the official yields throughout the whole series.

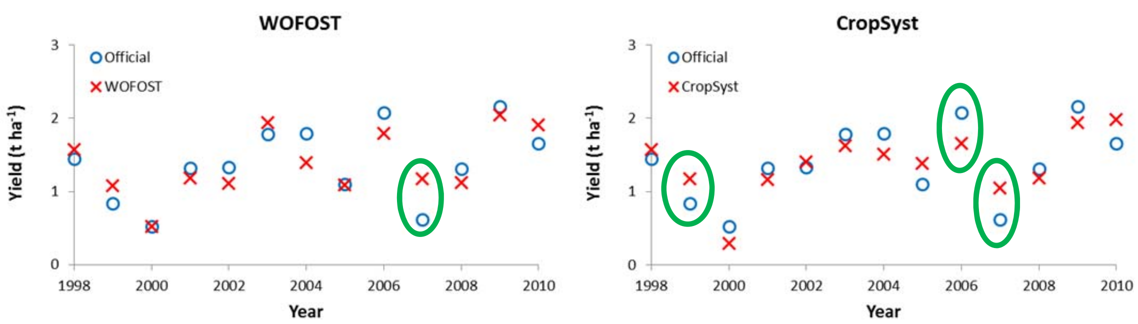

Figure 17 Multi-model soft wheat monitoring in Morocco; decade: maturity.

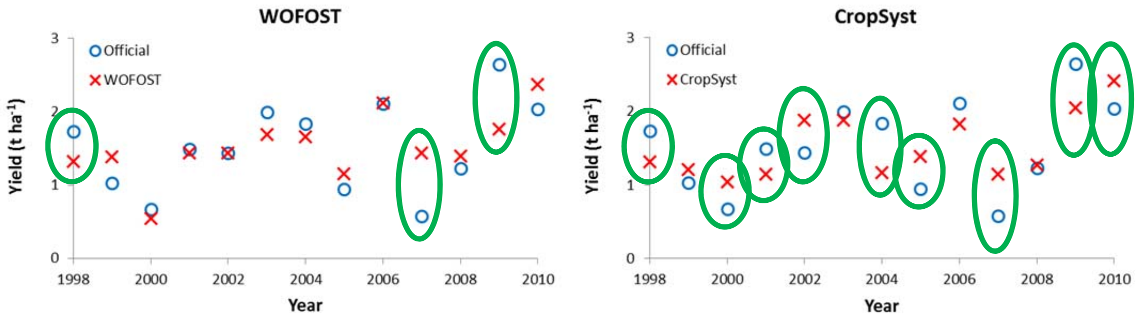

Figure 18 Multi-model soft wheat monitoring in Centre region; decade: maturity.

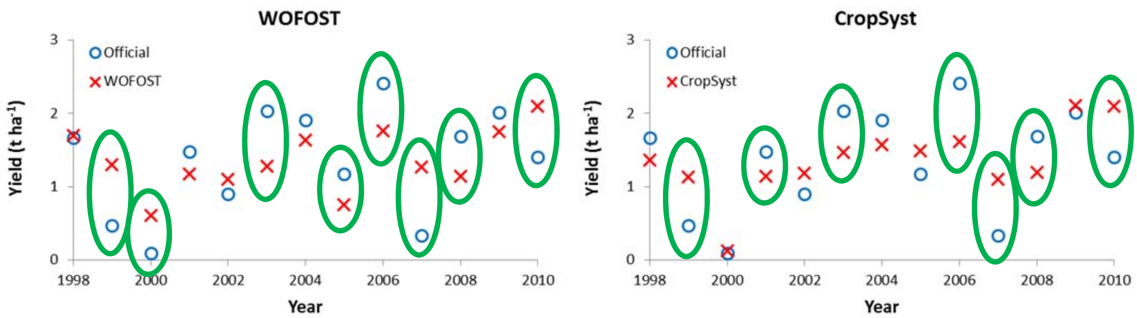

Figure 19 Multi-model soft wheat monitoring in Centre Nord region; decade: maturity.

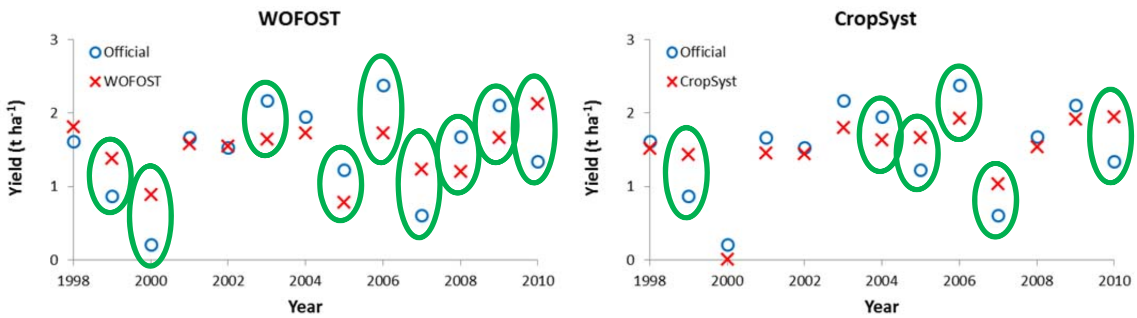

Figure 20 Multi-model soft wheat monitoring in Centre Sud region; decade: maturity.

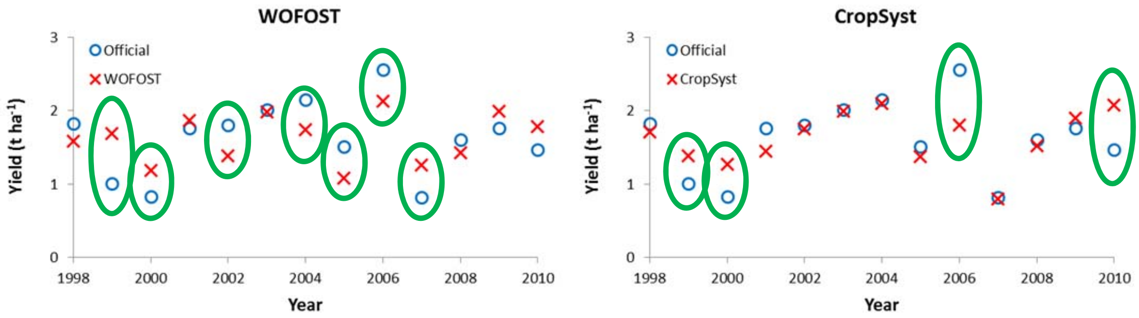

Figure 21 Multi-model soft wheat monitoring in Nord Ouest region; decade: maturity.

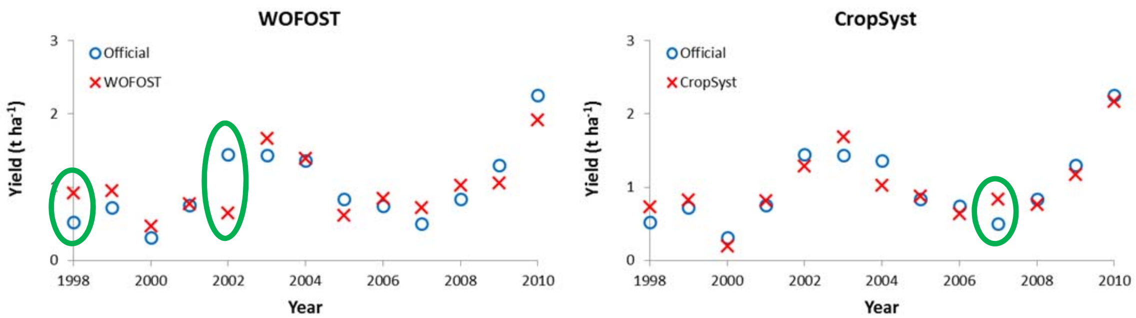

Figure 22 Multi-model soft wheat monitoring in Oriental region; decade: maturity.

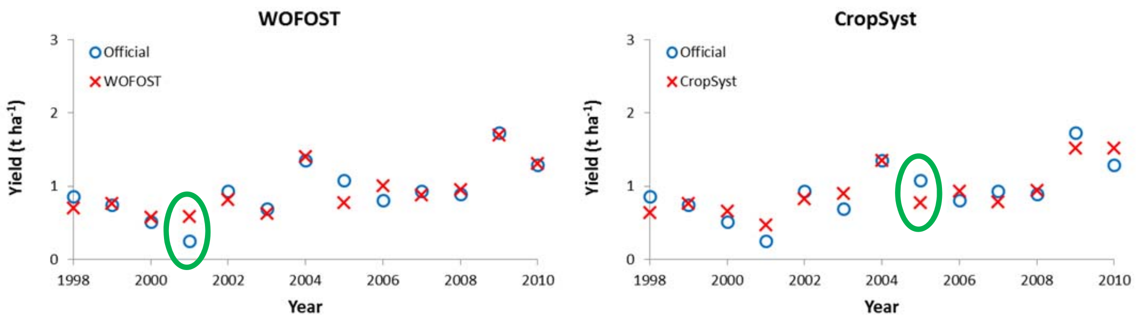

Figure 23 Multi-model soft wheat monitoring in Sud region; decade: maturity.

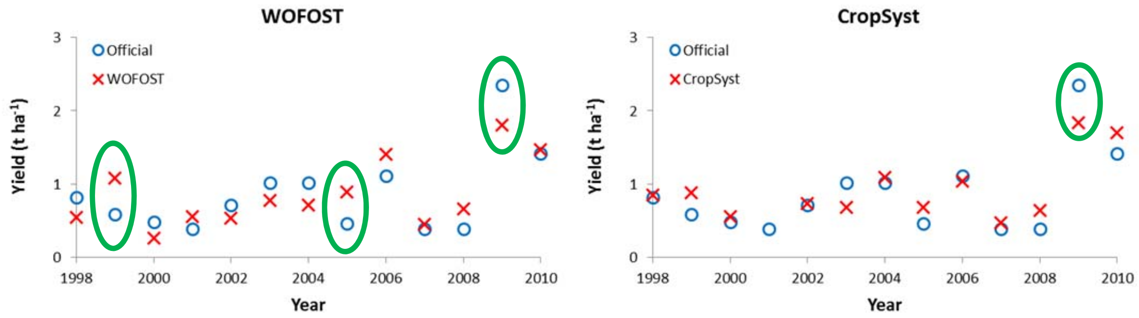

Figure 24 Multi-model soft wheat monitoring in Tensift region; decade: maturity.

Table 7 presents – for each region and model – the indicators selected by the stepwise regression procedure performed by the CGMS Statistical Toolbox.
The importance of temperature in affecting wheat productivity in Morocco discussed in section 3.1.2 is confirmed by the selection of the development stage code indicator in 12 out of 16 cases. The correlation with official yields is in most of the cases negative, since temperature in Morocco are usually more than favorable for wheat, and exceptionally warm seasons lead to shortening too much the crop cycle, to increasing crop evapotranspiration, and to heat stress during grain filling (Balaghi et al., 2008).

Table 7 Indicators selected by the stepwise regression performed between official yields and aggregated simulation outputs; forecast event triggered at maturity.

WOFOST	CropSyst
Morocco	
1 (PAGB)[a]	1 (PAGB)
5 (PDVS)[b]	5 (PDVS)
7 (n. infections)[c]	8 (PLAI)[d]
9 (LLAI)[e]	9 (LLAI)
Centre	
5 (PDVS)	1 (PAGB)
7 (n. infections)	3 (LAGB)[f]
8 (PLAI)	8 (PLAI)

9 (LLAI)	9 (LLAI)
Centre Nord	
1 (PAGB)	1 (PAGB)
3 (LAGB)	3 (LAGB)
5 (PDVS)	8 (PLAI)
7 (n. infections)	9 (LLAI)
Centre Sud	
1 (PAGB)	1 (PAGB)
3 (LAGB)	3 (LAGB)
7 (n. infections)	8 (PLAI)
8 (PLAI)	9 (LLAI)
Nord Ouest	
1 (PAGB)	1 (PAGB)
5 (PDVS)	3 (LAGB)
7 (n. infections)	5 (PDVS)
8 (PLAI)	9 (LLAI)
Oriental	
3 (LAGB)	1 (PAGB)
5 (PDVS)	3 (LAGB)
7 (n. infections)	5 (PDVS)
9 (LLAI)	9 (LLAI)
Sud	
5 (PDVS)	1 (PAGB)
7 (n. infections)	3 (LAGB)
8 (PLAI)	5 (PDVS)
9 (LLAI)	
Tensift	
5 (PDVS)	1 (PAGB)
7 (n. infections)	3 (LAGB)

8 (PLAI)	5 (PDVS)
9 (LLAI)	9 (LLAI)

[a]: potential aboveground biomass
[b]: potential development stage code
[c]: number of infection events
[d]: potential leaf area index
[e]: limited leaf area index
[f]: limited aboveground biomass

3.2.2. Forecast event triggered three decades before maturity

Results of the multi-model approach to durum wheat monitoring at maturity are shown in Tables 8 and 9, and in Figures from 25 to 32.

The heterogeneous and – in some cases – unsatisfying performances discussed for soft wheat are confirmed by the results obtained when the forecast event was triggered three decades before maturity (Table 8).

At national level, both the models did not exceed the values of 0.61 for R^2. The poorest performances were obtained in Centre Sud (R^2 = 0.39 for both models) and Nord Ouest regions (R^2 = 0.29 and 0.40 for WOFOST and CropSyst, respectively). The highest accuracy for soft wheat was again achieved in southern and eastern areas, where CropSyst allowed explaining 89% and 84% of the inter-annual yield variability in Oriental and Tensift regions, respectively.

CropSyst achieved the best values of the evaluation metrics in four regions out of seven.

Table 8 Multi-model soft wheat monitoring in Morocco; results of the cross validation for the forecast event triggered three decades before maturity. Bold-red indicates the best value for the metric.

Region	Trend	WOFOST	CropSyst
		R^2	
Morocco	Linear	0.61	**0.61**
Centre	No trend	**0.78**	0.64
Centre Nord	No trend	**0.49**	0.49
Centre Sud	No trend	0.39	**0.39**
Nord Ouest	No trend	0.29	**0.40**
Oriental	No trend	0.69	**0.89**
Sud	Linear	**0.72**	0.70
Tensift	Linear	0.74	**0.84**
		RRMSE (%)	
Morocco	Linear	22.53	**22.49**
Centre	No trend	**18.27**	23.37
Centre Nord	No trend	**36.28**	36.49

Centre Sud	No trend	31.88	**31.85**
Nord Ouest	No trend	25.28	**23.25**
Oriental	No trend	28.04	**17.06**
Sud	Linear	**20.61**	21.40
Tensift	Linear	31.58	**24.58**

Figures from 25 to 32 show the agreement between official and forecasted yields.
As already observed when the forecast event was triggered for soft wheat at maturity (see section 3.2.1), the behavior of the two models appears quite similar at national level (Figure 25). They presented indeed a satisfying reliability in most of the years, although they overestimated official yields in 1999 and 2010 and revealed an underestimating behavior in 2004.
The model reliability was discrete in the Centre region (Figure 26), with uncertainties observed in just three years for both the models (2006, 2009 and 2010 for WOFOST; 1999, 2005 and 2009 for CropSyst).
As discussed for the forecasting event triggered at maturity, the main problems were observed in the other central regions (Centre Nord, Centre Sud) and in the Nord Ouest one (Figures 27, 28 and 29, respectively), where further investigations are likely needed before the operational use of the monitoring system.
The situation is decidedly better for the regions Oriental (Figure 30), Sud (Figure 31) and Tensift (Figure 32), where both the models successfully captured the inter-annual variability of the historical series of official yields, although CropSyst usually assured the best performances in this part of the Country.

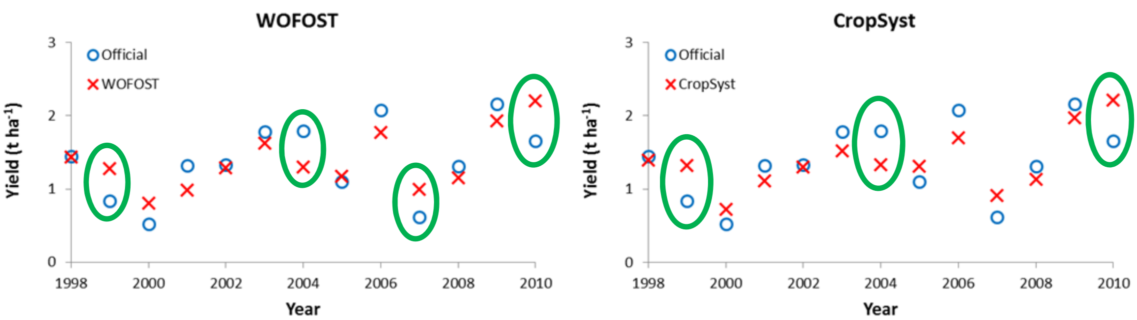

Figure 25 Multi-model soft wheat monitoring in Morocco; decade: 3 before maturity.

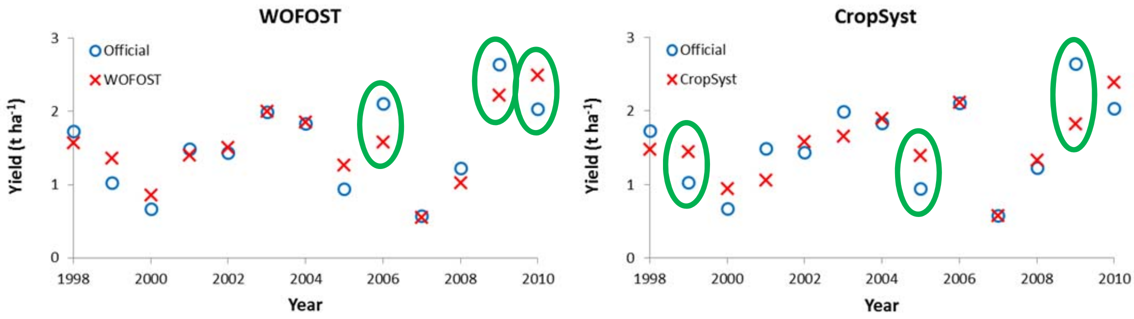

Figure 26 Multi-model soft wheat monitoring in Centre region; decade: 3 before maturity.

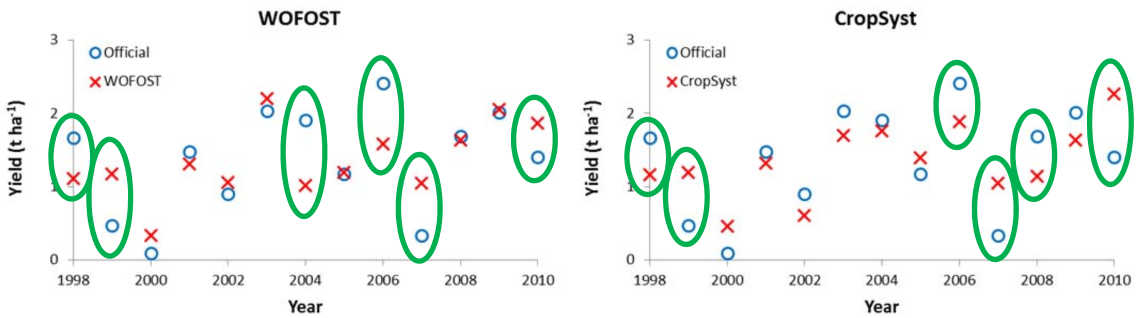

Figure 27 Multi-model soft wheat monitoring in Centre Nord region; decade: 3 before maturity.

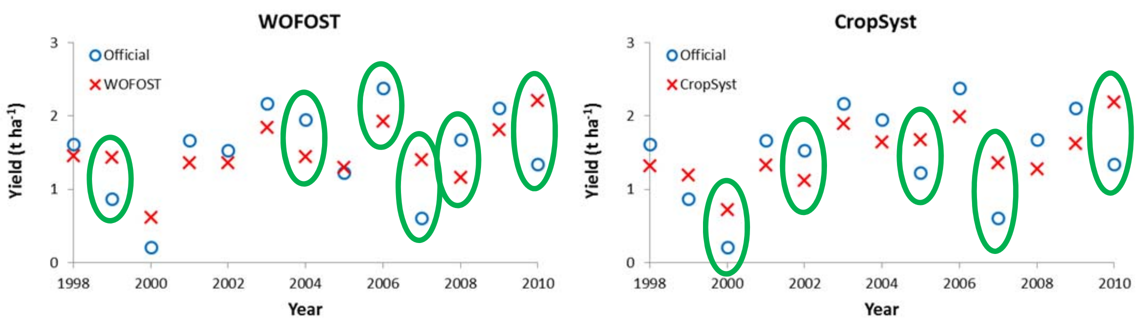

Figure 28 Multi-model soft wheat monitoring in Centre Sud region; decade: 3 before maturity.

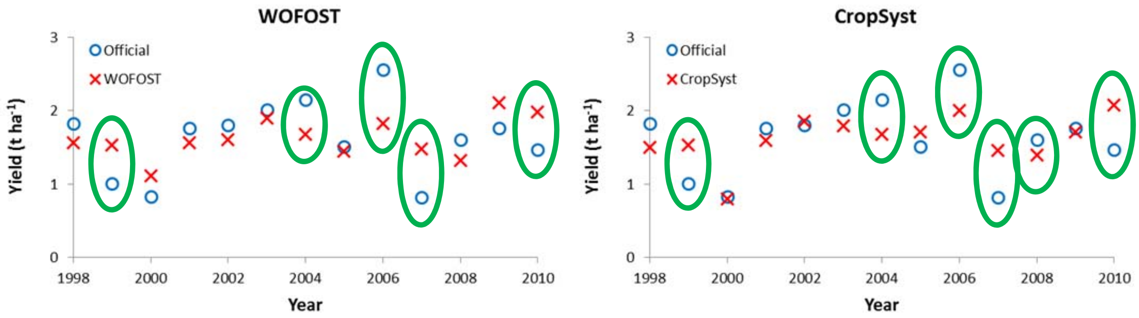

Figure 29 Multi-model soft wheat monitoring in Nord Ouest region; decade: 3 before maturity.

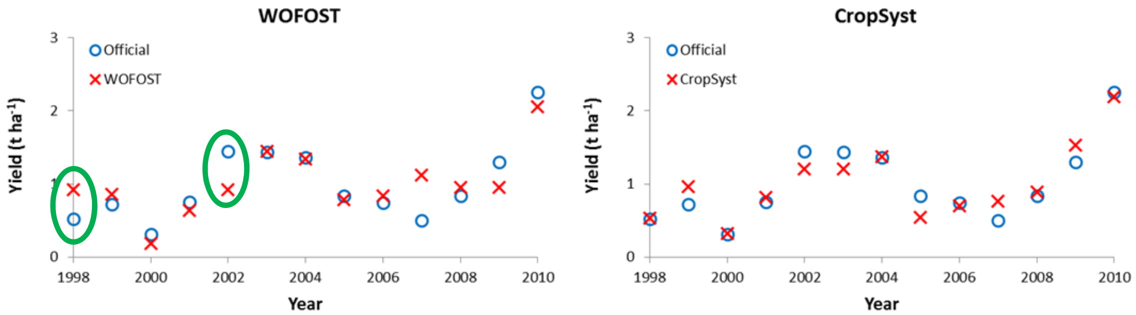

Figure 30 Multi-model soft wheat monitoring in Oriental region; decade: 3 before maturity.

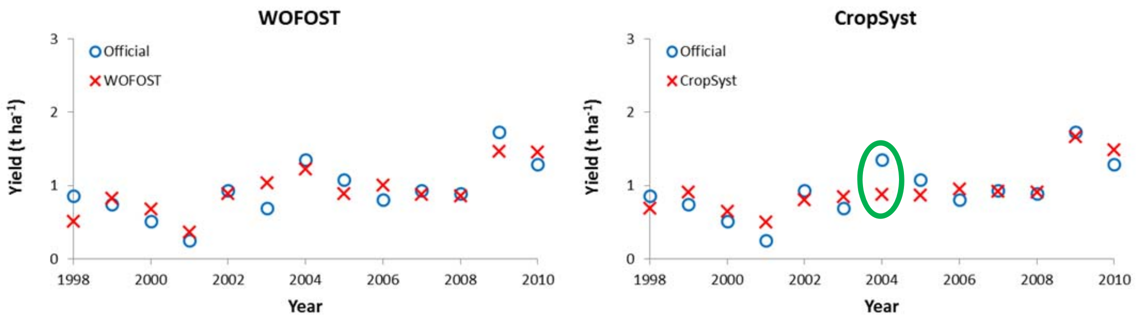

Figure 31 Multi-model soft wheat monitoring in Sud region; decade: 3 before maturity.

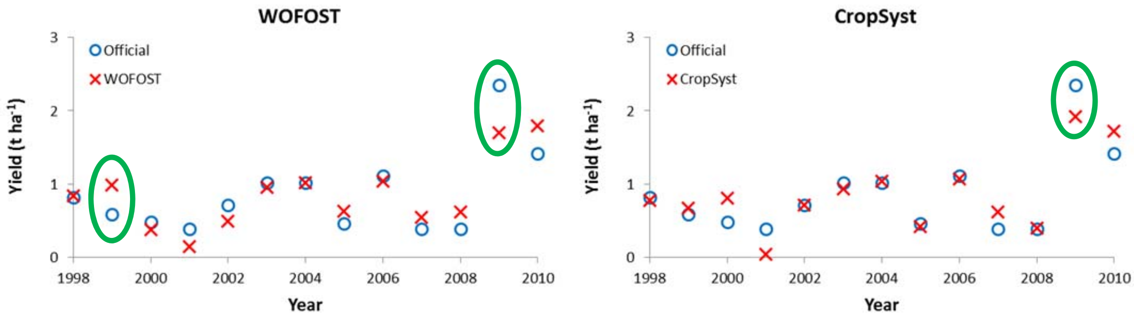

Figure 32 Multi-model soft wheat monitoring in Tensift region; decade: 3 before maturity.

Table 9 presents – for each region and model – the indicators selected by the stepwise regression procedure performed by the CGMS Statistical Toolbox.

Although the variability in rainfall amount and distribution – and thus water limited indicators – plays a major role in determining the inter-annual wheat yield fluctuations, development stage code (only driven by temperature in both the modelling approaches) and number of potential infections can be surely considered as crucial drivers for wheat productivity in the Country. They are indeed selected in 10 out of 16 cases (development stage code) and in five out of 16 cases (number of potential infection events).

Table 9 Indicators selected by the stepwise regression performed between official yields and aggregated simulation outputs; forecast event triggered three decades before maturity.

WOFOST	CropSyst
Morocco	
1 (PAGB)[a]	3 (LAGB)[b]
3 (LAGB)	5 (PDVS)[c]
7 (n. infections)[d]	8 (PLAI)[e]
8 (PLAI)	9 (LLAI)[f]
Centre	
1 (PAGB)	3 (LAGB)
3 (LAGB)	5 (PDVS)
8 (PLAI)	8 (PLAI)

9 (LLAI)	9 (LLAI)
Centre Nord	
1 (PAGB)	1 (PAGB)
3 (LAGB)	3 (LAGB)
8 (PLAI)	5 (PDVS)
9 (LLAI)	9 (LLAI)
Centre Sud	
1 (PAGB)	1 (PAGB)
3 (LAGB)	5 (PDVS)
7 (n. infections)	8 (PLAI)
9 (LLAI)	9 (LLAI)
Nord Ouest	
3 (LAGB)	1 (PAGB)
7 (n. infections)	3 (LAGB)
8 (PLAI)	5 (PDVS)
9 (LLAI)	9 (LLAI)
Oriental	
1 (PAGB)	3 (LAGB)
3 (LAGB)	5 (PDVS)
5 (PDVS)	8 (PLAI)
9 (LLAI)	9 (LLAI)
Sud	
1 (PAGB)	1 (PAGB)
3 (LAGB)	3 (LAGB)
7 (n. infections)	5 (PDVS)
8 (PLAI)	8 (PLAI)
Tensift	
3 (LAGB)	3 (LAGB)
5 (PDVS)	5 (PDVS)

7 (n. infections)	8 (PLAI)
8 (PLAI)	9 (LLAI)

[a]: potential aboveground biomass
[b]: limited aboveground biomass
[c]: potential development stage code
[d]: number of infection events
[e]: potential leaf area index
[f]: limited leaf area index

4. Conclusions

The multi-model approach to crop yield prediction was here tested in a different way compared to what the international modelling community is doing since few years within the AgMIP activities (Asseng et al., 2013). AgMIP is based on the parallel use of different models and on the use of statistics – e.g., the median – calculated on their output as predictors. Even in this case – and as we did for rice in Jiangsu (see E-AGRI report D33.2) – different models were run in parallel, although no statistics were computed on their outputs, and the best model was instead used in different regions, for different species (durum and soft wheat), and in different forecasting moments during the season.
The rationale behind this approach is that models markedly differing in the way physiological processes involved with crop growth and development are formalized could be more suitable under different conditions, regardless from the performances achieved during calibration and validation activities performed at field level.
The fact that CropSyst and WOFOST resulted more suitable under different conditions demonstrates the goodness of this approach.

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