Evaluation of downscaled DEMETER multi-model ensemble seasonal hindcasts in a Northern Italy location by means of a model of wheat growth and soil water balance

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ABSTRACT

This paper explores the new possibilities for early crop yield assessment at the local scale arising from the availability of dynamic crop growth models and of downscaled multi-model ensemble seasonal forecasts, and compares the use of the latter with other methods, based on crop growth models driven by observed climatic data only. The soil water balance model developed and used at ARPA Emilia-Romagna (CRITERIA) was integrated with crop growth routines from the model WOFOST 7.1. Some validation runs were first carried out and we verified with independent field data that the new integrated model satisfactorily simulated above ground biomass and leaf area index. The model was then used to test the feasibility of using downscaled multi-model ensemble seasonal hindcasts, coming from the DEMETER European research project, in order to get early (i.e. 90, 60, 30 days before harvest) yield assessments for winter wheat in northern Italy. For comparison, similar runs with climatology instead of hindcasts were also carried out. For the same purpose we also produced six simple linear regression models of final crop yields on within season (end of March, April, May) storage organs and above ground biomass values. Median yields obtained using downscaled DEMETER hindcasts always outperformed the simple regression models and were substantially equivalent to the climatology runs, with the exception of the June experiment, where the downscaled seasonal hindcasts resulted clearly better than all other methods in reproducing the winter wheat yields simulated with observed weather data. The crop growth model output dispersion was almost always significantly lower than the dispersion of the downscaled ensemble seasonal hindcast used as input for crop simulations.

1. Introduction

Operational agrometeorologists are often faced with the problem of providing early assessments of crop yields to farmers and to other agricultural stakeholders (WMO, 1982). They can do this with several methods, characterized by different scales of application and reliability levels (FAO, 1986; Supit, 1997). In Europe the use of dynamic crop growth models combined with statistical regression models for agricultural production monitoring and early assessment at the national and continental scales is now well established (Genovese, 1998).

In recent years seasonal forecasts are being placed more and more to the attention of farmers, planners and traders (Hartmann et al., 2002; Grifoni et al., 2003), that show a strong interest for them for obvious reasons: reliable seasonal forecasts could induce a sort of technical revolution in farming, farmland planning and food commodity trading, allowing to move from the current tactical use of short to mid-range weather forecasts to a strategic use of long-range climatic outlooks (Hoogenboom, 2002). The economic value of such a move is also being explored by research (Fox et al., 1999). The DEMETER project (Palmer et al., 2004) successfully set up a facility for multi-model ensemble seasonal hindcasting of the 1960-2000 period at the global scale, which constitutes a unique opportunity to evaluate this type of meteorological product in view of providing early crop yield assessments by means of a dynamic crop growth model.

In this work three methodologies were explored and compared: the first one relies on simple linear regression in order to assess final yield from above ground and storage organs biomass values simulated with a crop growth model driven by weather data up to a certain date (three, two and one months before harvest), the second one consists in running the crop model with weather data up to the mentioned dates, then substituting observations with synthetic weather data produced with a stochastic weather generator from local climatological statistics up to harvest date (i.e. following the methodology recently proposed by Bannayan et. al., 2003), finally the third one, similar to the former but with substitution of observations with downscaled multi-model ensemble seasonal forecasts.

2. Materials and methods

2.1. Climatic data

The data normally used for crop and soil water simulations at ARPA Emilia-Romagna are quality-checked daily total precipitation and daily extreme 2 m air temperatures. Other environmental variables like solar radiation and potential evapotranspiration are usually computed from the former by means of empirical formulas (Hargreaves, 1974; Donatelli and Marletto, 1994).

The area of interest for this study is approximately 130,000 km^2, located in northern Italy, between latitudes 43.72º and 46.14° N, and longitudes 7.20º and 13.20º E. The northernmost part of the study area is in the Alps, the central part consists of the Po river valley, surrounded by the Apennines to the south and the Adriatic Sea to the east.

A large set of measured daily precipitation data have been collected from European countries by the Mesoscale Alpine Programme (MAP, Frei and Schär, 1988). A subset of MAP data consisting of analysed daily precipitation covering northern Italy on a regular grid (0.3° x 0.22°) for the period 1966-1999 was used for this work.

Daily maximum and minimum 2 m temperatures covering the above mentioned area were instead made available from UCEA (Ufficio Centrale di Ecologia Agraria, Rome, Italy). The original UCEA analyses cover all the Italian region from 36° N to 47° N and from 7 °E to 18 °E on a regular 0.37° x 0.27° grid, for the period 1961-1999 (Girolamo and Libertà, 1990).

Because of the different spatial scales, an upscaling of the UCEA observations was performed so that the data were aggregated on the MAP grid. The precipitation distribution is highly non uniform in space, especially in the mountains. Major maxima (1500-1900 mm/yr) can be found, for example, over the Alps and over the Apennines, while minima (600-700 mm/yr) can be found in the Po river plain. The mean maximum temperature in the Po valley was between 16 and 18 °C, the minimum between 7 and 9 °C.

In addition to the above, synthetic daily data of precipitation and temperature needed for the “climatology” runs of the crop model were produced using the ClimGen weather generator (Stockle and Nelson, 1998) driven by observed climatic data from 1966 to 1990.

2.2. Seasonal forecasts and downscaling

The use of a multi-model ensemble system allows for uncertainties in model formulation to be included in the estimation of seasonal forecast probabilities (Harrison et al., 1996, Hagedorn et al., 2005). The seasonal forecasts used for this work come from the DEMETER system, consisting of seven comprehensive European global coupled atmosphere-ocean models installed at ECMWF (Palmer et al., 2004). All models produced hindcasts, i.e. forecasts of past years, within the 1958-2001 time range, though only two of them covered it completely. However outputs for all models are available from 1980 to 2001. The Demeter system runs four times per year, starting at 00 GMT on the first of February for spring, May for summer, August for autumn and November for winter. Nine seasonal 6-month forecasts (members) are produced for each model and season, with a spread on initial conditions created using wind stress and sea surface temperature perturbations.

For a number of practical reasons, mainly connected with missing climatological data and limited human resources to carry out the downscaling, we used the spring hindcasts from only four of the DEMETER models (CNRM from Météo-France, UKMO from the UK Met Office, SCWF from ECMWF, SMPI from MPI), with nine members and two downscaling replicates. Downscaling from the global coarse grid of DEMETER to the finer one needed for our local application was carried out at DMI (Danish Meteorological Institute) using the singular value decomposition technique applied to DEMETER monthly means and standard deviations of 2 m temperatures and to specific precipitation statistics (probability of a wet day, wet day rainfall amount, lag-one autocorrelation of occurrence of a wet day, Feddersen and Andersen, 2005). Daily temperatures and rainfall amounts, to be used in the crop model, were obtained from a weather generator (Richardson, 1981). The needed climatological basis was provided from the observational datasets described above (2.1).

2.3 The CRITERIA/WOFOST model

During the DEMETER project an already existing soil water balance modelling system (CRITERIA, Marletto et al., 1993; Marletto and Zinoni, 1996) was integrated with routines from WOFOST 7.1 (WOrld FOod Studies, Supit et al., 1994), a crop growth simulation model developed in the Netherlands by Kees van Diepen et al. (1989) and currently in use at the European Joint Research Centre (JRC), in the framework of the continental crop yield forecasting system CGMS (Genovese, 1998).

CRITERIA is a mathematical model with a geographical interface for the evaluation of cropped soil water balance in the regional territory (see Appendix A for a short description). The model, driven by meteorological, soil and crop data, computes daily soil water balance state and auxiliary variables like actual evaporation and transpiration, surface and subsurface runoff, deep drainage and others, presenting the results on graphs, tables and geographical maps. Recently routines modelling the balance and transport of nutrients like nitrogen and phosphorus in agricultural soils have been added to the model, in order to address the environmental pollution problems caused in our region by excessive fertilization on vulnerable soils (Zinoni et al., 2001). There is also a simpler version of CRITERIA called “Banco di Prova” (test bench) that allows to test the mathematical model routines with data from a specific station, without geographical interface; this version is often used for the implementation and test of new routines and was extensively used for this work.

CRITERIA was specifically developed as a multi-layered model in order to address agri-environmental issues (i.e. the risks of ground water pollution by nitrates or pesticides) where accurate computation of water flows and balance is essential. Moreover, this structure allows to interface the model to the dataset provided by the Regional soil bureau, where hundreds of detailed soil profiles are available. (Filippi and Sbarbati, 1994).

After analysing the WOFOST 7.1 crop model structure, the mathematical routines for the simulation of crop production have been implemented into the CRITERIA system (Marletto et al., 2001). Translation of code from Fortran to Basic was necessary because the latter is the coding language for the CRITERIA model. However, some important differences from the original WOFOST were introduced: the wheat development and growth model we implemented uses a LAI (Leaf Area Index) vs. heat accumulation forcing function that was already in use in CRITERIA instead of the WOFOST original LAI increase computations, which are part of a positive feedback loop initially driven by temperature, then by radiation, generally affected by a very strong dependence on initial dry matter values, which can be measured during experiments but are difficult to provide in an operational setup. Moreover, due to the greater detail of CRITERIA in representing the behaviour of water in our soils, other output variables from the latter model (potential and actual evaporation and transpiration, rooting depth) were used to force crop growth.

Input requirements for the CRITERIA/WOFOST integrated model include weather and soil conditions, crop characteristics and management data. The minimum weather data requirements are daily extreme temperatures and precipitation. Soil inputs include at least texture, organic matter and bulk density for all soil layers.

The new integrated model simulates two production situations: non-water-limited (P1) and water-limited (P2). The P1 situation is driven only by air temperature, daylength, global radiation and crop characteristics (e.g. leaf area dynamics, assimilation characteristics, dry matter partitioning, etc.). The P2 water-limited situation is characterized by the same factors of P1 with the addition of soil water availability, depending on rainfall and evapotranspiration, soil physical properties and root characteristics.

The development stage (DVS) of the crop is computed by integrating the daily development rate, a linear function of air temperature and daylength. Temperature is however the main environmental factor affecting development rate. Higher temperatures accelerate it, leading to shorter growing periods. Physiological plant age is defined by the development stage, which governs the allocation of dry matter to plant organs, i.e. roots, leaves, stems and storage organs. The most important phenological change is from vegetative to reproductive stage, which determines a large redirection of dry matter allocation to the storage organs. For many annual crops development stage can be conveniently expressed with a dimensionless variable, having the value 0 at seedling emergence, 1 at flowering and 2 at maturity (van Heemst, 1986). Development stage is linearly related to the temperature sum, expressed in daydegrees (°D), that is the sum of daily temperatures above a base temperature, which changes for wheat from 0 °C (emergence-anthesis) to 9 °C (anthesis-maturity). Development rate is then the ratio of daily daydegrees over a phase-specific threshold temperature sum.

Crop growth depends on gross assimilation, which on its turn depends on the intercepted photosynthetically active radiation (PAR). The intercepted PAR is determined by the level of incoming sunlight and the leaf area and canopy structure of the crop. The daily rate of potential gross photosynthesis is computed from the absorbed radiation and the photosynthetic characteristics of the canopy profile. The total instantaneous gross CO_2 assimilation rate is driven by intercepted light and is computed integrating the instantaneous canopy CO_2 assimilation rate over the canopy depth. Daily gross CO_2 assimilation rate is obtained by integrating the total instantaneous rate over the day. Both computations are carried out by means of the simple and fast Gaussian numerical integration method (Goudriaan, 1986). In the P2 situation reduction of transpiration due to water or oxygen stress results in a proportional reduction of gross assimilation.

Part of the carbohydrates produced are used for maintenance respiration, while the rest are converted at a cost (growth respiration) into structural biomass of plant organs. Maintenance costs depend on weight and on the maintenance coefficients of leaves, stems and storage organs, and increase with temperature. As described before, the partitioning of biomass to plant organs depends on the development stage of the crop.

For an updated and complete description of WOFOST as implemented at JRC see Supit and van der Goot (2003).

2.4. Site characterization and crop measurements

The experimental data used for model evaluation were collected in 1994-1995 at the experimental station of the Istituto Sperimentale Agronomico, located in San Prospero, Modena, Italy, (44° 47' N, 11°02' E, 23 m asl). The soil of the site is a silty-clay, classified as Vertic Ustochrept, with a plant available water holding capacity of about 150 mm m^{-1} of depth.

The sampled wheat crop, cv. Centauro, was sown on 26 October 1994, with a standard row sowing machine, with a density of 450 kernels m^{-2}, and distances of 0.13 m within the rows. The preceding crop was maize. The crop was fertilized with 100 kg P_2O_5 ha^{-1}, applied as super phosphate on 19 October during seedbed preparation, and 200 kg N ha^{-1}, applied as urea on 10 March 1995. Weeds were controlled chemically at the end of the winter. Meteorological data, used for model evaluation, were measured continuously in the meteorological area besides the experiment. Data were recorded electronically.

Leaf area and aboveground dry matter were measured weekly starting from the 9th of March to the 5th of June 1995. Destructive samples of 0.52 m^2 (i.e. a continuous trait of 2 linear meters of 2 contiguous rows) were collected. Two independent samples were collected at random in representative areas without edge effects within a large plot of 775 m^2. The sampled plot belongs to a multi-annual field experiment comparing several crop rotations started on 1994 and still ongoing. No rotational effects were observed at this early phase of the trial (Ceotto, 1999).

The surface of individual leaves was measured using a leaf area meter (DELTA-T Devices) and cumulated to obtain the overall leaf area, then referred to the sampled surface in order to calculate LAI. The dry weights of sampled biomass were determined after oven drying at 65 °C for 48 h, and then referred to the sampled area.

2.5. Model calibration and evaluation

In the environment on study winter wheat is sowed at mid October, emergence occurs at the beginning of November, and the crop remains normally dormant until the beginning of March.

Physiological maturity occurs between mid June and the end of June, and harvest usually starts 10 to 15 days later, to allow grain moisture to come down to values suitable for mechanical harvesting. In simulating the crop it was assumed that the emergence occurred on November 1.

A calibration of the model was not carried out, due to the lack of detailed experimental data. However for the description of winter wheat in northern Italy calibrated assimilate allocation coefficients from Marletto and van Keulen (1984) where used, instead of the original ones provided by Boogaard et al. (1998), which were not well suited to our conditions due to the simulation starting date used (January 1 instead of mid-October), and to the start of biomass accumulation in storage organs at anthesis, an assumption that does not take into account the translocation to seeds of dry matter accumulated in stems and leafs before anthesis. The main crop parameters and AFGEN (arbitrary function generator) tables used for crop simulation are presented in Table 1.

Simulated values of LAI and total above ground biomass (AGB) were compared with observations in order to assess the accuracy of model prediction. The comparisons of predicted and observed above ground biomass (AGB) and LAI are shown in Figure 1. Following Willmott (1982), the accuracy of simulations was assessed using the coefficient of determination (R^2), derived from the regression of observed to predicted AGB and LAI, the root mean square deviation (RMSD), which represents a mean weighted difference (mean distance) between predicted and observed data, and the mean bias error (MBE), which is the difference between the means of simulations and measurements. The values assumed by the statistical indices are reported in Table 2. The results indicate a good accuracy for AGB whilst larger discrepancies were observed between measured and simulated values of LAI. This behaviour is in agreement with the results of Bannayan et al. (2003). In fact these authors simulated winter wheat yield in the U.K. using the CERES-Wheat model and reported the largest differences between measured and simulated values of LAI, in comparison to AGB. However, such a verification of results with independent field data looks satisfactory for both AGB and LAI.

2.6 DEMETER hindcasts evaluation approach

The calibrated and adapted WOFOST/CRITERIA model was used to simulate winter wheat water-limited (P2) yields from 1977 to 1987, in a point of the Po valley (44° 6' N, 11° 1' E), using combinations of observed weather data and downscaled DEMETER hindcasts, trying to establish the crop yield predictive power of the latter as a substitute for actual weather data. A combination consists of running crop growth simulations with observations up to a certain date and with climatology or downscaled DEMETER hindcasts up to wheat harvest date (usually end of June in the plains of Northern Italy). Three combinations were tried, aiming at prediction of final yields three, two and one months before harvest. To do so observed weather data were used for simulations up to March 31, April 30 , and May 31, respectively. From the latter dates onwards the model was driven either by climatology (using an "ensemble" of ten daily data series produced with the stochastic weather generator CLIMGEN) or by downscaled multi-model ensemble DEMETER hindcasts provided by DMI.

Median yields predicted with climatology and with DEMETER hindcasts were also compared, in terms of determination coefficient and root mean square errors, with predictions obtained from simple linear regressions between total or storage organs biomass simulated up to the above mentioned dates and final yield simulated with weather observations only.

3. Results and discussion

Downscaled DEMETER hindcasts from the February runs of the years 1977-1987 were used to simulate crop growth with the CRITERIA/WOFOST model in the last months (AMJ, MJ, J) of the winter wheat growing season at a location near Modena, Italy. Hindcasts from four global coupled models, nine replicates and two daily weather generator series were used for each of the three prediction exercises for a total of more than 200 model runs (Figure 2). This resulted in an increase of crop yield predictive power: median P2 (water-limited) yields predicted with downscaled DEMETER hindcasts were always performing equal or better in terms of determination coefficient

R^2 (0.62, 0.73 and 0.97 for the AMJ, MJ and J combinations resp.) than predictions obtained from linear regressions between partial simulation values of storage organ and total biomass at the above mentioned dates and final yields simulated with observations weather data only (0.44, 0.34, 0.90 with storage organ biomass and 0.63, 0.41, 0.90 with total above ground biomass as independent predictors of final yield). Combination runs carried out with climatology (10 replicate series of daily data from a stochastic weather generator) performed better (0.67) than the downscaled DEMETER hindcasts in the AMJ run, equal (0.73) in the MJ run, and worse (0.92) in the June run. Moreover the downscaled DEMETER hindcasts used in June instead of observations accurately predicted final wheat yields in terms of RMSD (0.53 t ha^{-1}) not only better than the linear regressions on storage organ (0.87) and total biomass (0.89) but also significantly better than climatology (0.90). No clear "winner" could be found between the four global models used, as SMPI slightly outperformed the other models and the ensemble in the AMJ experiment, the CNRM did best in the MJ, but all four and the ensemble did practically the same in J. See Tables 3 and 4 for complete comparisons.

In terms of MBE the median yield predictions obtained with individual models and with the ensemble hindcasts always underestimated final crop yield for all combination dates, with MBE values roughly about half the RMSD in all experiments. Climatology shows an opposite behaviour, with positive MBEs and smaller MBE/RMSD ratios.

Figure 3 shows an interesting result obtained comparing the normalized spreads or dispersions of precipitation from the DEMETER downscaled hindcasts and the resulting CRITERIA/WOFOST winter wheat yields, in terms of the ratio of interquartile range over the median. Our model clearly tends to damp out the input dispersion and this effect is already visible in the AMJ experiment (Fig. 3a) where yields are more dispersed than precipitation only in two years out of eleven. The damping effect grows in MJ and is dramatic in J, where the model has been run with the longest observation series and shows the greatest inertia, reacting very little to the dispersion of the precipitation input.

The relative insensitivity to precipitation input in June could also be related to the fact that in the location of study crop growth usually stops before the end of the month.

We can conclude that this work shows the practical feasibility of using properly downscaled multi-model ensemble seasonal forecasts from global coupled models for the sake of predicting crop yields one or more months before harvest, even at the local scale where ARPA agrometeorologists work; in addition, when downscaled seasonal forecasts are used in combination with observed weather data to drive a crop growth and water balance model like CRITERIA/WOFOST, the normalized spread of the predicted crop yield distribution tends to be significantly lower than that of the meteorological input.

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Appendix A

The CRITERIA model

In this appendix a short description of the CRITERIA model is provided. The model describes the dynamics of water in agricultural soils in the presence of crops. It is based on the approach of Driessen (1986) and Driessen and Konijn (1992) but assuming a multilayered soil and explicitly computing approximate values of daily, actual evaporation and transpiration, water flows between layers, deep drainage, runoff and subsurface runoff. The model allows to include the effect on infiltration of low permeability layers, which are of special relevance in the southern Po plain of Emilia-Romagna, where silty and clayey soils are abundant (Filippi and Sbarbati, 1994).

In the model maximum daily transpiration Tm (mm d^{-1}) is computed by the expression

$$Tm = Et_0\ TC\ (kcref - 0.33) / 0.67 \qquad (A.1)$$

In this formula Et_0 represents the reference potential transpiration (mm d^{-1}) while TC is a turbulence coefficient determined with the expression

$$TC = 1 + (TCM - 1)\ (kcref - 0.33) / 0.67 \qquad (A.2)$$

where TCM is the maximum level of TC, dependent on the crop and essentially coincident with the maximum value of the crop coefficient kc proposed by Doorenbos and Kassam (1979), while

$$kcref = 0.33 + 0.67\ e^{-0.8\ LAI} \qquad (A.3)$$

where LAI is the leaf area index (-). Actual transpiration (Te, mm d^{-1}) is assumed nil for very humid soil, that is when water content θ (-) is above half the range between field capacity and saturation, i.e. above the value

$$\theta_{0.5} = 0.5\ (\theta_s - \theta_{fc}) \qquad (A.4)$$

where θ_s and θ_{fc} represent respectively the water content (-) of the rooted zone at saturation and at field capacity, while for water contents above field capacity and below the above limit the following expression holds:

$$Te = Tm\ [\theta_s - \theta_{0.5} - \theta] / \theta_{0.5}. \qquad (A.5)$$

Below field capacity

$$Te = \max\ (Tm, MUR) \qquad (A.6)$$

where

$$MUR = (\psi_{leaf} - \psi) / (R_{plant} + R_{root}). \qquad (A.7)$$

In the last expression MUR (maximum uptake rate, mm d^{-1}) depends on the water potentials ψ_{leaf} (tabulated per crop, mm) and ψ (derived from water content by means of the soil water retention curve, mm), and also on the specific resistances R_{plant} (resistance to flow in the plant, tabulated per crop, d) and R_{root} (d), which in turn is inversely proportional to rooting depth D (m) and hydraulic conductivity k (mm d-1) as follows:

$$R_{root} = 10 / kD. \qquad (A.8)$$

Maximum infiltration I_{max} (mm d^{-1}) is computed daily for every layer with the following approximate solution of the general flow expression (Driessen, 1986):

$$I_{max} = S_0 (1 - \theta/\theta_s)\, t^{-0.5} + A \qquad (A.9)$$

where S_0 and A are texture class specific coefficients (standard sorptivity, mm $d^{-0.5}$, and transmission zone permeability, mm d^{-1}) and t (d) is time since last rain.

Actual infiltration rate I in turn depends on an empiric reduction coefficient Irc ranging from 0 (impermeability) to 1 (standard soil conditions) as follows:

$$I = I_{rc}\, I_{max}. \qquad (A.10)$$

Deep drainage occurs when flow from the deepest soil layer considered (usually at 2 m depth) is greater than zero.

Runoff (mm d^{-1}) consists of water at the soil surface exceeding the surface water holding capacity S (mm), which is computed using the following expression:

$$S = (d + C) \sin^2(\sigma - \phi)\, (\cot(\sigma + \phi) + \cot(\sigma - f)) / (4 \sin\sigma \cos\sigma \cos\phi) \qquad (A.11)$$

where ϕ is field slope angle, σ is the clod angle, d is surface roughness (mm) and C is a crop specific and LAI dependent vegetation water holding capacity (mm). Surface roughness depends on tillage type and decreases linearly with time from the last tillage operation.

Subsurface runoff SR (mm d^{-1}) occurs in the presence of surplus water (i.e. water content greater than field capacity) in soil layers higher than the drainage ditches' bottom depth and its rate is assessed in CRITERIA using the following expression:

$$SR = I_{max} (\sin\phi + h (L + w) / 2 wL) \qquad (A.12)$$

where L and w represent the length and width (m) of an idealized rectangular field and h is the soil layer's height (m).

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Table 1. a) Maximum leaf CO_2 assimilation (AMAX) as a function of development stage DVS. b) Reduction factor (TMPFTB) of AMAX as a function of average temperature Ta. c) Reduction factor of gross assimilation rate (TMNFTB) as a function of minimum temperature Tm. d) Fractions of total dry matter allocated to roots (FRTB), leaves (FSTB), stems (FLTB) and storage organs (FSOB), as a function of development stage (DVS).

a)

DVS	AMAX
0.0	35.83
1.0	35.83
1.3	35.83
2.0	4.48

b)

Ta	TMPFTB
0.0	0.01
10.0	0.60
15.0	1.00
25.0	1.00
35.0	0.00

c)

Tm	TMNFTB
0.0	0.00
3.0	1.00

d)

DVS	FRTB	FSTB	FLTB	FSOB
0	0.5	0	0.475	0.025
0.2	0.29	0	0.685	0.025
0.35	0.19	0	0.785	0.025
0.4	0.175	0.045	0.755	0.025
0.5	0.135	0.325	0.515	0.025
0.6	0.1	0.535	0.32	0.045
0.7	0.075	0.59	0.22	0.115
0.8	0.05	0.58	0.125	0.245
0.9	0.03	0.45	0.07	0.45
1	0.02	0.25	0.02	0.71
1.1	0.01	0.09	0	0.9
1.2	0	0	0	1
2	0	0	0	1

Table 2. Statistical indices from the crop growth model validation with independent field data.

	Above ground biomass (AGB)		Leaf area index (LAI)
Year	1994	1995	1995
RMSD	1749	931	0.93
MBE	1520	-256	0.23
R^2	0.97	0.97	0.59

LEGEND
RMSD: root mean square deviation (in kg ha^{-1} for AGB and adimensional for LAI)
MBE: mean bias error (in kg ha^{-1} for AGB and adimensional for LAI)
R^2: determination coefficient

Table 3. Indices and coefficients of linear regressions of final wheat yields on partial simulations biomass values.

Prediction date	Independent variable	RMSD (kg ha^{-1})	MBE	R^2	a	b
April 1	BSO	2083	-0.041	0.44*	15.0360	4568.1
”	AGB	1695	0.009	0.63*	2.2593	-221.9
May 1	BSO	2256	-0.045	0.34ns	1.7002	3872.3
”	AGB	2135	0.266	0.41*	1.5254	-6337.2
June 1	BSO	873	0.080	0.90**	1.2427	-500.4
”	AGB	887	0.598	0.90**	1.2357	-9859.1

LEGEND
Prediction date: date of linear regression prediction using partial simulation values of biomass as independent variable.
BSO (biomass of storage organs): crop yield is predicted with linear regression on storage organ biomass at the prediction date.
AGB (above ground biomass): crop yield is predicted with linear regression on total biomass at the prediction date.
RMSD: root mean square deviation (kg ha^{-1})
MBE: mean bias error (kg ha^{-1})
R^2: determination coefficient
ns non significant
* significant at the 0.05 probability level
** significant at the 0.01 probability level
a, b: linear regression coefficients

Table 4. Evaluation of the performance of climatology, four individual DEMETER models and ensemble downscaled hindcasts in reproducing the final wheat yields simulated with observed weather data (Modena, Italy, 1977-1987).

Combination date	Model	RMSD	MBE	R^2
April 1	Climatology	1701	413	0.67**
”	CNRM	1935	-578	0.57**
”	SCWF	2013	-629	0.54*
”	SMPI	1741	-314	0.63**
”	UKMO	1967	-830	0.60**
”	Ensemble	1838	-627	0.62**
May 1	Climatology	1481	152	0.73**
”	CNRM	1495	-748	0.79**
”	SCWF	1829	-404	0.59**
”	SMPI	1736	-452	0.65**
”	UKMO	1661	-764	0.72**
”	Ensemble	1585	-665	0.73**
June 1	Climatology	905	386	0.92**
”	CNRM	583	-252	0.97**
”	SCWF	464	-209	0.98**
”	SMPI	509	-203	0.97**
”	UKMO	500	-172	0.97**
”	Ensemble	535	-210	0.97**

LEGEND
Combination date: end of observations and start of climatological or hindcast data.
Model: source of weather data to complete growing season simulation.
Climatology: final median crop yield predicted with synthetic climatological data produced with a weather generator.
Ensemble: final median crop yield predicted with downscaled ensemble hindcasts.

Figure captions

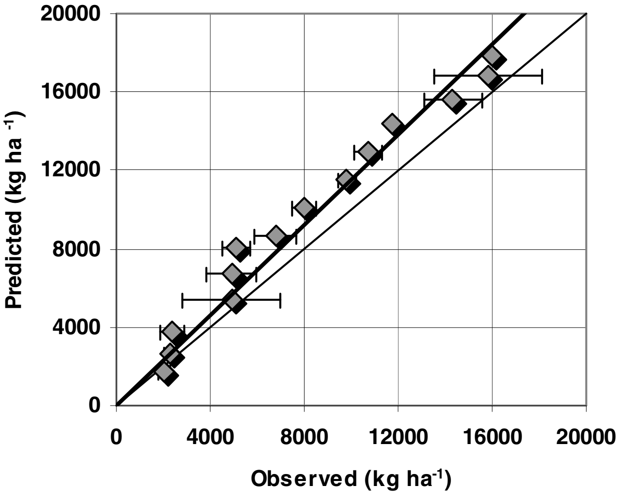
Figure 1. Comparison of winter wheat above ground biomass (a, 1994; b, 1995) and leaf area index (c, 1995) simulated with the CRITERIA/WOFOST model driven by temperature and precipitation data measured at the experimental station of San Prospero, Modena, Italy with field measurements carried out on the same spot. The reference 1:1 line is also visible.

Figure 2. Box and whiskers distributions of predicted water-limited wheat yields (kg ha^{-1}) simulated using downscaled multi-model ensemble DEMETER hindcasts for the years 1977-1987 in a location near Modena, Italy. Wheat yields simulated with observed weather data and median yields simulated with climatology are also provided for comparison.

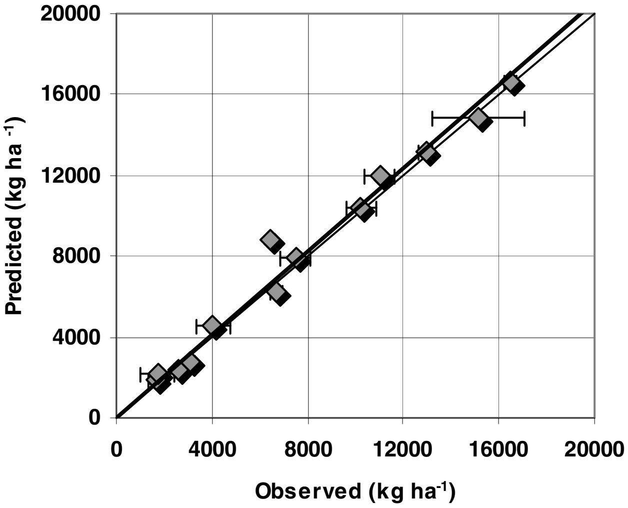
Figure 3. Normalized dispersion of downscaled precipitation outputs from DEMETER and of outputs from the crop yield model driven by the latter. Normalized dispersion is here defined as the ratio of the interquartile distance (P75 – P25) of every distribution over the respective median P50, where P stands for percentile. Plot (a) refers to three months of DEMETER data (AMJ), (b) refers to two months (MJ) and (c) to one month (J). Years and location as in Figure 2.

Figure 1

a - Above Ground Biomass 1994



b - Above Ground Biomass 1995



c - Leaf Area Index 1995

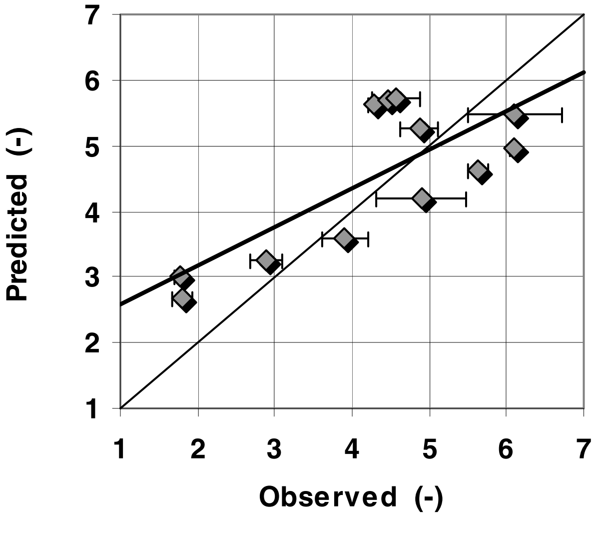
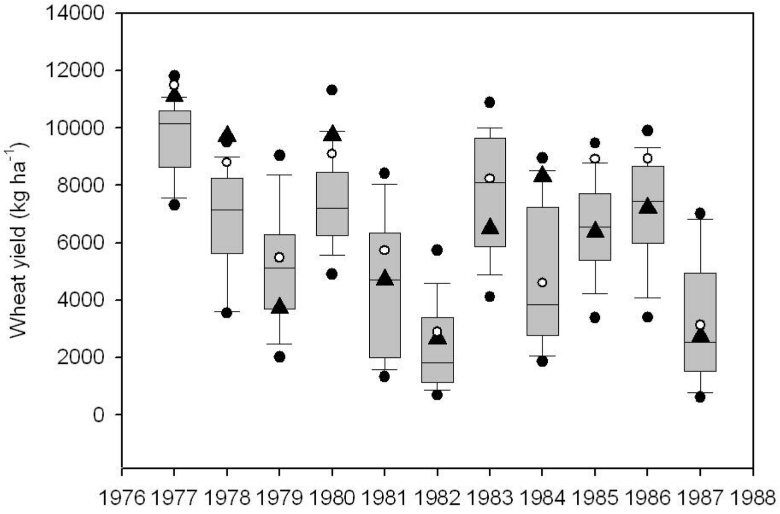
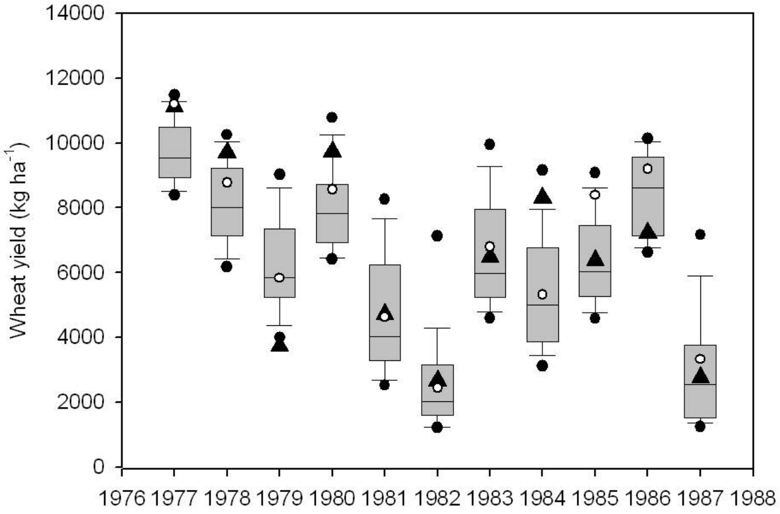


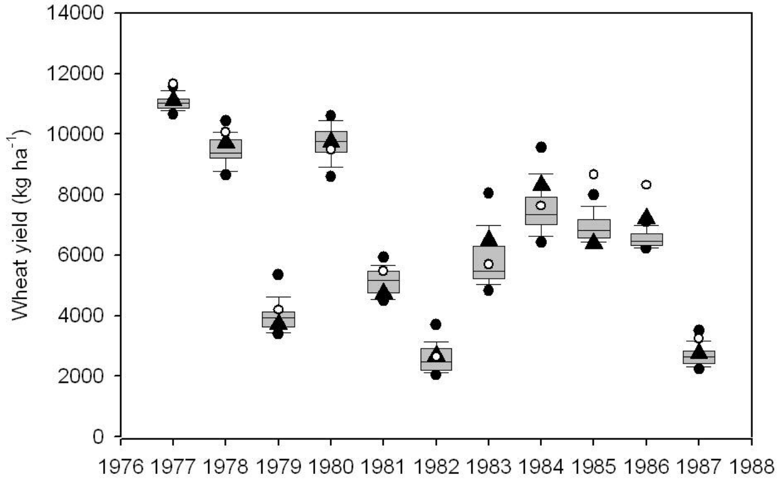
Figure 2



(a) AMJ



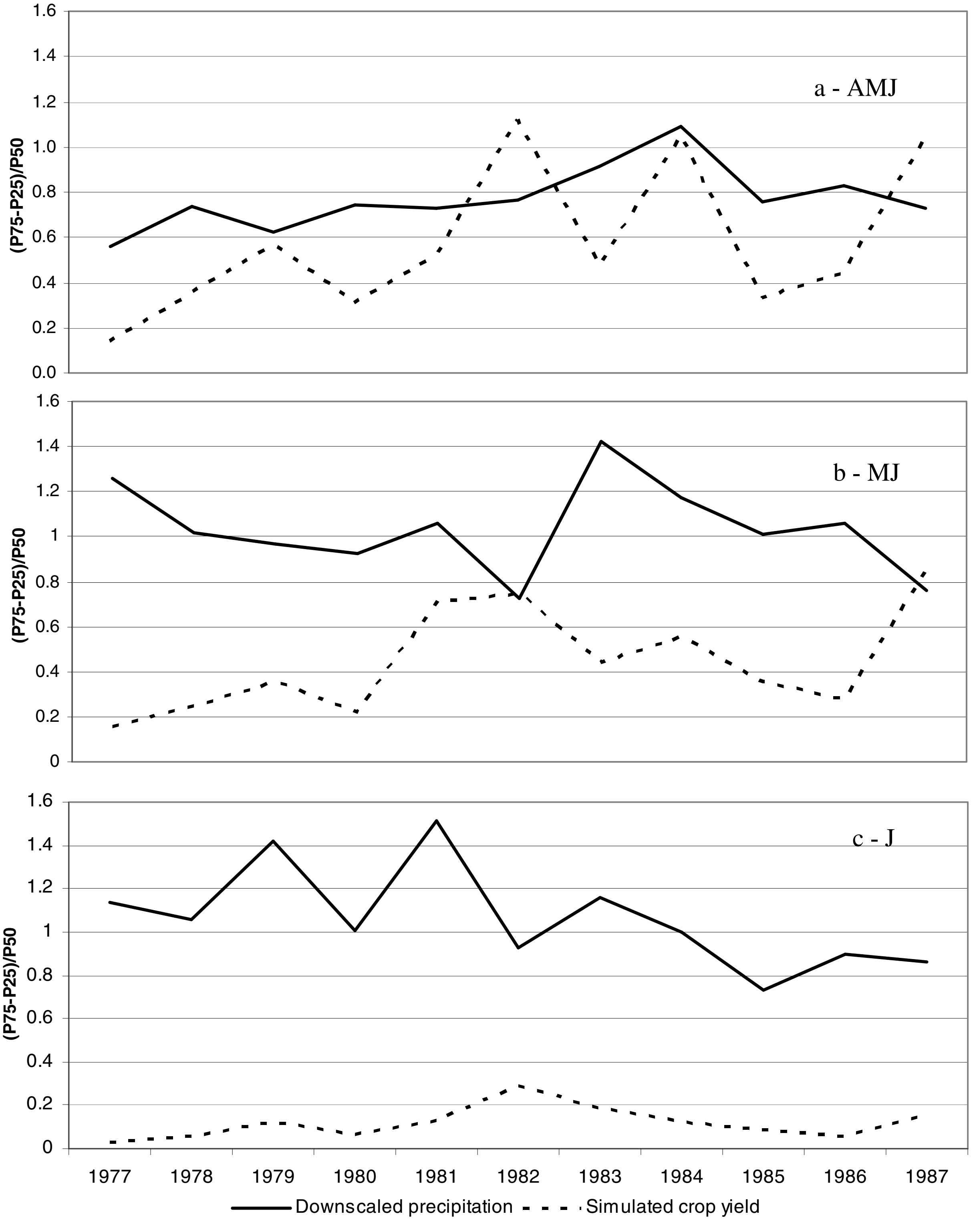
(b) MJ



(c) J

▨ Demeter (5, 10, 25, 50, 75, 90, 95 %)
▲ Observed weather
○ Climatology (median)

Figure 3


a - AMJ
b - MJ
c - J
(P75-P25)/P50
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
Downscaled precipitation
Simulated crop yield