Field scale water-use efficiency inherent variability and options for crop selection and management

Richter G.M., Lawlor D., Latiri K., Acutis M., Qureshi K.

in

Rana G. (ed.), Mastrorilli M. (ed.), Albrizio R. (ed.).
WEMED workshop: how to advance the knowledge on water use efficiency in the Mediterranean region ?

Bari : CIHEAM
Options Méditerranéennes : Série A. Séminaires Méditerranéens; n. 72

2007
pages 93-100

FIELD SCALE WATER-USE EFFICIENCY INHERENT VARIABILITY AND OPTIONS FOR CROP SELECTION AND MANAGEMENT

G. M. Richter*, D. W. Lawlor*, K. Latiri, M. Acutis*** and K. Qureshi******
*Rothamsted Research, Harpenden, AL5 2JQ, UK;
**INRAT, Ariana, TUNISIA;
***Dip Produzione Vegetale, Università di Milano, Italy,
****University of the Punjab, Pakistan

SUMMARY - Rising atmospheric [CO_2] can increase photosynthesis and yield of crops, but rising temperature could increase transpiration more strongly. Water-use efficiency (WUE, total dry matter or yield produced per unit of water used) is the result of these two intensely intertwined processes. WUE is therefore implicitly variable due to effects of climatic/environmental variation, management and crop properties, which sheds some doubt on its usefulness. In a classical field experiment for spring barely using a rain-shelter, WUE in 1979 differed from that of a drier year (1976) due to the difference in vapour pressure deficit (VPD). We present results using an improved photosynthesis based crop model describing meteorological and biophysical processes in various climates, simulating growth, yield and water use. For typical field conditions in the UK, temporal variability of WUE was greater than spatial variability. The model can also quantify the effects of management, e.g. sowing date. A sensitivity analysis ranks the importance of the model's crop parameters according to environment. Sowing date was the most sensitive management decision to achieve large yields. In the Mediterranean (Tunisia), parameters for the establishment (early vigour) of Durum wheat were the most important factors for increasing production and using water most efficiently. Overall, WUE was an indicator less sensitive than yield, and it seems that focus on WUE obscures the relevance of yield determining factors.

Key words: Agro-meteorology, modelling, parameter estimation, sensitivity analysis

IS WUE A USEFUL INDICATOR OF CROP PRODUCTION UNDER WATER LIMITATION?

Globally, demand for water in food production will increase strongly, while predicted changes in climate and environment contain conflicting messages: Rising atmospheric [CO_2] will increase carbon-fixation through photosynthesis, and under isothermal conditions transpiration will decrease because stomatal conductance to water vapour decreases due to the effect of increased CO_2 in reducing stomatal opening. However, with rising temperature, transpiration and crop water use could increase more strongly, so water-use efficiency (WUE) could drop. Under water shortage, yield and its components vary greatly but WUE remains similar (Day *et al*., 1987; Day *et al*., 1978; Lawlor *et al*., 1981). Comparison of different years showed that part of the variation was due to differences in climatic conditions (Day *et al*., 1987). Thus, WUE is not a good indicator of crop production. In Mediterranean cropping systems, drought resistance is an important selection criterion, and all traits that enhance water uptake and its "economic" use are crucial for yield formation (Solomon and Labuschagne, 2003). Thus, large WUE is regarded as a measure of drought resistance and selection for it is a way of obtaining crops with enhanced yield under drought conditions. However, excessive focus on WUE could over-simplify the problem and fail to identify the factors by which water-limited crop production can be optimized. Crop phenology and growth dynamics, water uptake, total biomass and yield are all affected by the water availability and severity of water deficits (Farre and Faci, 2006; Turner, 2004). Therefore, a dynamic analysis of factors determining crop production and water uptake and loss is required. It is essential to show how important these crop and environmental traits and parameters are and how they rank in terms of relative importance. In complex systems, models are valuable as they allow testing of the sensitivity of the parameters which would help trait selection (Campolongo *et al*., 1999; Saltelli *et al*., 2000).

The overall objective of this paper is to draw attention to the ambiguity of the term "water-use efficiency" and the need looking at both, absolute yield and water use (efficiency) together, and the factors determining each of them. For this we, firstly, demonstrate the large variation of yield over a single WUE for a particular crop under different management and - if normalised with respect to vapour pressure deficit, VPD - even for different environments. Secondly, we show how a simulation model of crop production and water use helps to understand the process of yield formation and illustrate possible ways to improve yields under dry conditions. We also discuss how variability of crop parameters and input data at the field scale could result in uncertainty of crop yield estimates.

METHODOLOGICAL ISSUES

Definitions: Usually, one defines the physiological water-use efficiency as yield or dry matter production per unit water used [g dry matter kg^{-1} water], in which the surface evaporation from soil and crop is not separated from transpiration through the plant. A more precise term is transpiration efficiency, TE, [g dry matter kg^{-1} water transpired] (Kemanian *et al*., 2005). Employing transpiration instead of evapotranspiration allows a more physiologically relevant estimate of efficiency (Day *et al*., 1987). Day *et al.* (1987) also proposed normalising the WUE, dividing by the leaf-air vapour pressure difference, Δe_A. Using a simulation model developed in the STAMINA project (Richter *et al*., 2006) we showed for the UK that TE is approximately twice the WUE, due to evaporation from soil and crop surfaces in the early and late season, respectively. In a wet year (e.g. 2004) a large proportion of the total water loss could come from water intercepted on the leaf surface.

LESSONS FROM A CLASSICAL FIELD EXPERIMENT

Data from rain-shelter experiments in the UK during 1976 (Day *et al*., 1978) and 1979 (Day *et al*., 1987), with drought of different intensity induced at different periods in crop growth, show the differences in yield and water use caused by drought under different weather conditions. In short, 1976 was a hot, dry year with large crop to atmosphere (VPD) while 1979 was cooler, with less radiation and smaller VPD. Spring barley (*Hordeum vulgare*, L. cv Julia) was sown at a density of 290 plant m^{-2} on 1 April 1976 and 18 April 1979, and harvested on 29 July and 31 August, respectively. Date of anthesis was about 10 days later in 1979. Irrigation treatments ranged from Zero to Full irrigation (368 mm) in 1976, including pre- (BA) and post anthesis (AA) treatments with 98 and 170 mm, respectively. In 1979, irrigation was 0, 50, 125 and 240 mm for pre-, post-anthesis and throughout growth, respectively. Water use was quantified from soil-water depletion using a neutron probe (to 1.5 m depth).

Total dry matter (Figure 1a) ranged from 5 to 13 t ha^{-1} and grain yields from 2.8 to 5.6 t ha^{-1} in 1976 and from 3.7 to 6.1 t ha^{-1} in 1979. Average WUE based on yield was 1.5 g L^{-1} in 1976 and 2.2 g L^{-1} in 1979, but with approximately constant WUE in each year. When WUE was normalised for the leaf-air vapour pressure difference, Δe_A , the relationship between water consumption and dry matter production was represented by a single slope (Figure 1b).

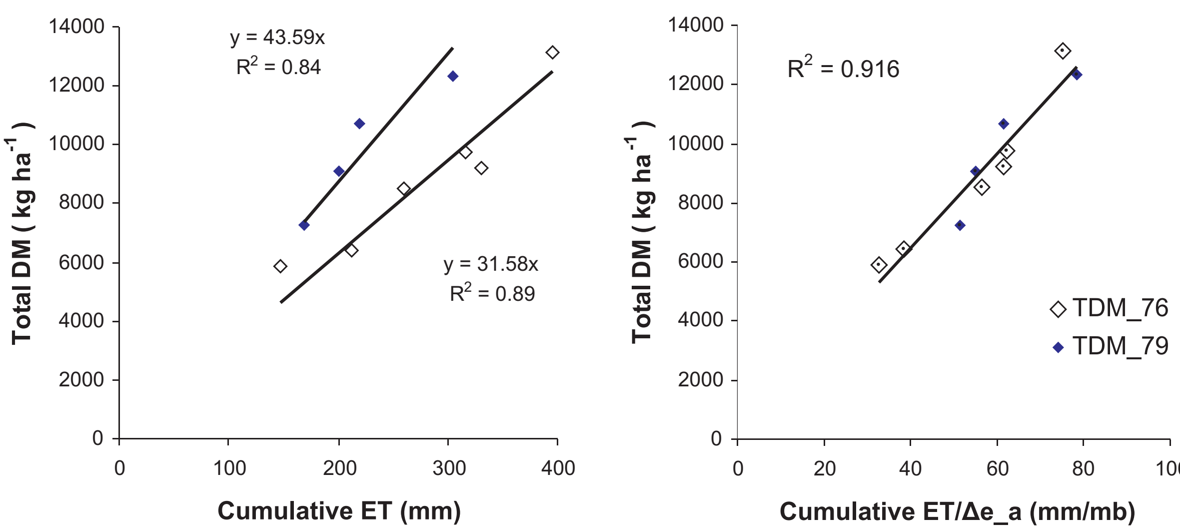

Figure 1. Relationship between total dry matter and (a) cumulative evapotranspiration ET and (b) ET normalised over leaf-air vapour potential difference measured for spring barley in the Rothamsted rain-shelter experiments during summer 1976 and 1979; adapted from Day *et al*. (1987)

The WUE based on yield (data not shown) varied greatly between treatments especially because timing of drought affected the harvest index and was related to stress during grain filling. Timing of drought affected yield components, decreasing the sink strength by reducing the number of ears per hectare ($p< 0.001$) and number of grains per hectare ($p < 0.05$) with decreasing irrigation in the order Full > BA ~ AA > Zero. Particularly, stress before anthesis reduced number of tillers, ears and kernels per ear (Lawlor et al., 1981). Pre-anthesis irrigation increased grain number which resulted in reduced grain size (and yield) in a dry year (Lawlor *et al.*, 1981) while, in 1979, grain size was similar (n.s.) under less stress (Day *et al.*, 1987).

So, what is the conclusion of this for the Mediterranean? Obviously, WUE is not a constant for a crop. We need to account for difference in the environment (vapour pressure), and it is essential to consider not only WUE but absolute water loss and yield. Then we will see more clearly the variation of WUE and yield due to different levels of irrigation, or other management practices. Selection for increased WUE based on grain yield would increase yield consistently with ranking of cultivars for drought susceptibility indices (Solomon and Labuschagne, 2003). Timing of irrigation affects the sink strength because it alters the number of grains per area, and while early application may increase grains and be beneficial in a year with adequate water later, it may decrease yields in a year with later drought when grain filling cannot be sustained.

One needs to realize that TE and WUE comprise two variables, and therefore they are not parameters in the true physiological or physical meaning. It is more important to identify what determines the variables constituting TE or WUE, yield and its components being the most important in economic terms. Additionally, one must quantify water uptake and the amount of water used in different processes.

MODELLING CROP GROWTH FOR YIELD PREDICTION

Quantitative models of soil, plant and atmospheric processes have been widely applied to crop growth, and used for testing hypotheses, designing cropping systems, predicting environmental impacts, and assessing risks to food security. A generic crop model, based on crop development, CO_2 assimilation, and agro-meteorology, has been specifically designed to describe physical impacts on crop performance, e.g. effects of climate/weather and terrain (Richter *et al.*, 2006). Among other crops, the model was calibrated for winter wheat in the UK and results were presented for the variability of yields (Richter *et al.*, 2005a) and WUE (Richter et al., 2005b) at field and small catchment scale. Its spatial variability (CV) was below 10 % during years with average rainfall but 20 % under drought, while it varied by more than 25 % over 30 years.

Here we present two applications of the model, (a) to irrigated winter wheat in Pakistan (Qureshi *et al*., 2007) and (b) rain-fed durum wheat in Tunisia (Latiri-Souki *et al*., 1998); calibration is described elsewhere (Richter *et al*., 2006, Chapter 3.2).

For irrigated winter wheat grown at Faisalabad, Pakistan, modelling was based on information concerning development (Ishaq *et al*., 2001) and grain filling (Khan *et al*., 2004a). Crops sown at 6 different dates (15 Oct 1991 to 15 Jan 1992) were used to calibrate the parameters of the vernalisation sub-model, dynamics of LAI and growth rate. Model parameters were evaluated using yield data for the same location between 1993 and 2002 (Khan *et al*., 2004b).

In summary, it was crucial to reproduce the pattern of crop development, namely anthesis date and grain filling duration, resulting from delayed sowing date. Based on all years and sowing dates the predicted yields were close to the observed (Figure 2a). The residual mean square error (RMSE) was less than 1 t ha^{-1}, and the bias was small (0.3 t ha^{-1}); most of the error could be related to the first and last sowing dates. Clearly, simulated WUE decreased significantly with delayed sowing date, on average from 1.6 to 0.76 g L^{-1} decreasing to 47 % (Figure 2b) with standard deviation about 0.25 g L^{-1}, however yield dropped more clearly to less than 40 % of the yield at first sowing.

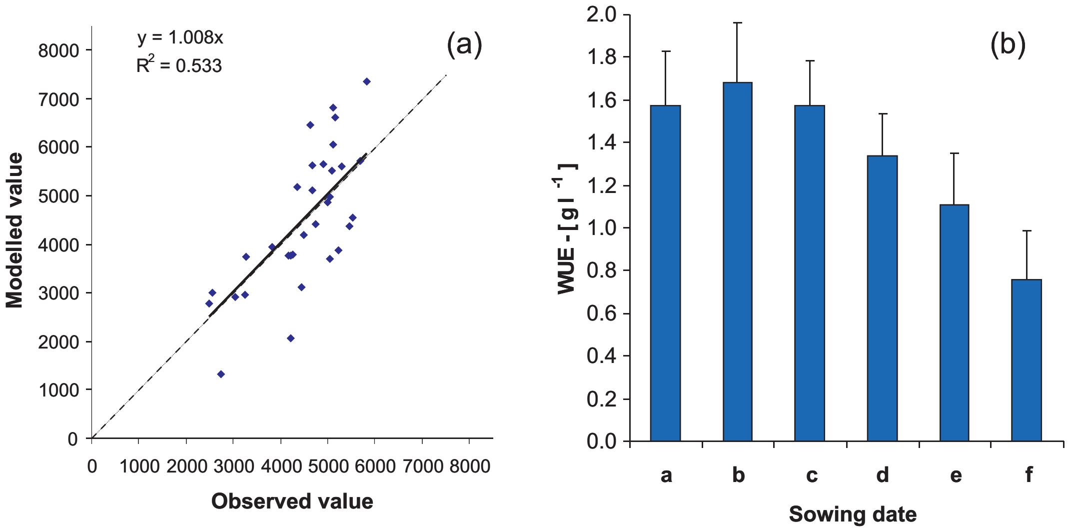

Figure 2: Modelling irrigated winter wheat in Pakistan sown between 15 Oct "a" and 15 Jan "f"; (a) model evaluation between 1992 - 2002 and (b) predicted average WUE

DETERMINANTS OF YIELD MODEL SENSITIVITY ANALYSIS

Sensitivity analysis is a standard method in model development and calibration and here we follow the method originally proposed by Morris (Saltelli *et al.*, 2004). The parameter sensitivity was determined for yields of Durum wheat (DW) at Nabeul, Tunisia on a sandy soil. The analysis used weather of the season 1990/91, sowing date was DoY 345 (11 December); no irrigation was applied. More details can be found in (Latiri-Souki et al., 1998) and in the STAMINA report (Richter et al., 2006).

For the sensitivity analysis, a total of 31 parameters were selected, plus sowing date which is very important in risk assessment studies (Richter and Semenov, 2005). The parameters could be grouped into six parameter classes, phenology, partitioning, establishment or early vigour, vigour, water stress and, finally, senescence (Table 1).

Table 1. Parameter groups and parameter name selected for the Sensitivity Analysis from the crop parameter table

Parameter groups	***Parameter***
Development	Growing degree days (e.g. to anthesis, grain filling)
	Base temperatures (T_{base} for emergence and maturation)
	Vernalization requirements
Partitioning	Root/shoot-ratio
	Allocation to leaves, stem, storage (grain)
Establishment	Management, e.g. sowing, N-fertilization
(early vigour)	Initial LAI, temperature coefficient for GLAI
	Specific Leaf Area
Vigour	Potential photosynthetic rate at light saturation
(photosynthesis)	Initial light conversion factor (photosynthetic efficiency)
Senescence	Age dependent leaf death
	Death rate of leaf area
Stress sensitivity	Coefficient of logistic water stress response function

For all parameters, mean values together with plausible standard deviation (SD) were chosen from the literature and earlier calibrations, and for the analysis 8 trajectories and 6 levels were chosen for each parameter. The variable tested was the change of yield per change of parameter (var = Δ yield / Δ parameter). Results are displayed as mean (μ*) and standard deviation (σ) of the Morris sensitivity (Figure 3). For the parameter groups μ* and σ were averaged (see Table 2).

RESULTS OF THE SENSITIVITY ANALYSIS FOR TUNISIAN DURUM WHEAT

Out of 32 parameters tested, 29 were of definite importance to yield formation. The range of μ* and σ spanned several orders of magnitude. The most sensitive management variable was the sowing date (μ* = 9000), the least important parameters were those describing the temperature response curve of CO_2 assimilation (μ* = 15). The direct parameters of CO_2 assimilation, however, were highly important (> 3000 for the CO_2 potential assimilation rate at light saturation, ~700 for initial light use efficiency). Among the top 15 ranks of sensitivity five parameters were related to early growth (Figure 3), four to plant development, and two each to vigour (photosynthesis) and senescence (beginning of wilting and wilting rate). Other parameters, which defined the leaf death as a response to self-shading, had no effect.

Parameters representing the response to water stress ranked number 12 and number 18. Changes in the partitioning parameters did not affect yield to any great extent; this included also the parameters of translocation. Changing the rate of root elongation had no effect, which is a surprising result at first sight, but seems plausible for a winter-sown crop which starts out in a moist soil.

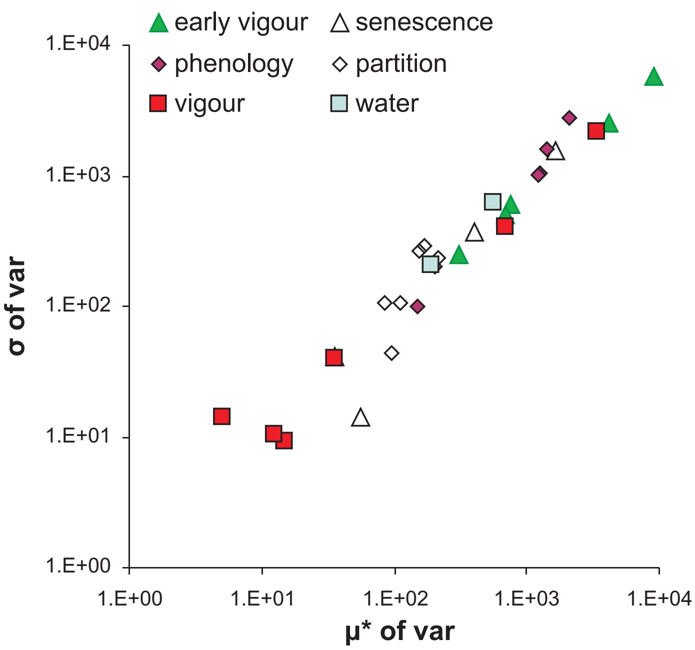

Figure 3. Graphical display of Morris sensitivity measures (μ*, σ) for 29 input parameters of the crop model applied to yield of durum wheat grown in Tunisia (1990/91); three parameters with “0” sensitivity were omitted because of logarithmic scale

Averaging the parameter groups, the overall ranking according to mean sensitivity (μ*) shows (Table 2) that parameters describing early vigour (emergence, initial LAI, establishment, light interception in terms of specific leaf area (SLA) and temperature factor for GLAI) had the greatest impact on yield. Parameters that describe phenology were almost as important, with the base temperature for maturation (which had been set to 9 ± 3 °C) most important, which needs further attention in research.

Table 2. Ranking of parameter groups according to mean Morris sensitivity (μ*) in relevance for yield formation of Durum wheat

Group	Average μ*	Average σ
Early vigour	3024	1932
Phenology	1063	1121
Vigour/photosynthesis	591	380
Water stress	380	415
Senescence	362	326
Partitioning	138	175

WHAT DO WE LEARN FROM THE SENSITIVITY ANALYSIS (SA)?

The sensitivity analysis for the crop growth model applied to wheat in Tunisia emphasises the importance of early crop establishment. This confirms findings of other research on wheat (Botwright *et al.*, 2002; Turner, 2004) and also for other crops, like sunflower (Aguera *et al.*, 1997; Villalobos *et al.*, 1996) in the Mediterranean.

Also, the SA highlights the importance of getting the phenology of a crop right, to maximise the period of grain filling. This is critically determined by anthesis date and speed of maturation, both of which ranked highly in terms of Morris sensitivity. These are important in Mediterranean conditions (Hafsi *et al*., 2003) and may also become a problem under climate change because senescence could increase with rising CO_2 and temperature (Manderscheid *et al*., 2003).

Use of the model to evaluate which factors determine water use, crop production and thus WUE, may be improved. There are possibly some artefacts in the SA:

- The *a priori* range of parameters may be too small assuming 5 % as the standard deviation of the mean value (e.g. root elongation 0.012 ± 0.0006 mm d^{-1}).
- Sensitivity is linked to a specific environment and particular weather data.
- Morris method is a first screening method that identifies the most sensitive parameters with few model runs, but uncertainties remain about exact ranking.

OVERALL DISCUSSION AND CONCLUSIONS

We have demonstrated that WUE is not a crop specific constant, but depends also strongly on the environment, particularly on VPD and radiation, which determines crop (leaf) temperature. These usually vary with location and season, and high WUE alone is neither a guarantee for high yield nor for water-saving. The emphasis on improving efficiency of crops to reduce water use whilst increasing production is essential, but focus on WUE should not result in a neglect of the underlying processes.

We considered here that a more efficient three-step approach to select better crop varieties relative to expenditure of water requires certain key measurements: (1) quantifying water loss over the season, crop phenology, yield and its components over time, (2) performing a sensitivity analysis for yield. Ultimately, one needs to model these for a range of environmental conditions.

Crop modelling, with well calibrated and tested process-based models provides a way to evaluate the interactions between crop and environment. It indicates crop characteristics most likely to improve production relative to water, and therefore useful for variety selection. From a practical point of view, models may be used to guide husbandry for optimum production and indicate variability in particular areas.

Yield is a function of process dynamics and sink-source relations, and timing, severity and duration of stress and plant growth and yield must be considered (Legg *et al.*, 1979). Early growth is most severely affected by water stress, as early drought reduces tiller and leaf numbers and size (source) and ears and grains (sink). After these growth stages, alleviation of stress normally does not reverse these effects. Drought tolerant crops and genotypes achieve higher yields by conserving water before and using more water after anthesis (Solomon and Labuschagne, 2003) or extracting water from deeper soil layers (Farre and Faci, 2006).

The sensitivity analysis for our model confirmed that parameters related to early vigour, time and speed of establishment (Botwright et al., 2002), increase of LAI are crucial. It reduces unproductive water loss, improves light interception and photosynthesis. Fast establishment is essential for optimum growth, which also requires adequate nutrients, particularly N (Latiri-Souki *et al.*, 1998). All features of early vigour increase the rate of water flux through the plant and the absolute CO_2 assimilation.

Surprisingly, parameters for carbohydrate allocation and partitioning, which determine HI, were not found to be sensitive for yield formation. This may have to be looked at again because the literature shows clearly that short-straw varieties have been beneficial to cereal selection in arid zones (Baenziger *et al.*, 2004). Furthermore, parameters for sink size, e.g. tiller and grain number, have not been included in this model.

The SA emphasises the necessity to record important information, such as emergence and initial leaf size or LAI, and critical development stages in any field experiment. Often only anthesis and harvest dates are recorded with inadequate physiological detail. This weakens the analysis of processes relating yield to crop traits and the environment.

It would be interesting to further clarify how lack of information affects the application of crop models increasing its predictive uncertainty. The selective calibration procedure reducing the number of parameters to match yields should be replaced by an automatic procedure (Van Oijen *et al.*, 2005).

ACKNOWLEDGEMENTS

Senior author thanks the organisers to invite him for this presentation, we acknowledge funding by the European Commission (QLK-5-CT-2002-01313). Rothamsted receives grant-in-aid from the UK Biotechnology and Biological Sciences Research Council.

REFERENCES

Aguera, F., Villalobos, F.J. and Orgaz, F., (1997). Evaluation of sunflower (Helianthus annuus, L.) genotypes differing in early vigour using a simulation model. European Journal of Agronomy, 7 (1-3): 109-118.

Baenziger, P.S., McMaster, G.S., Wilhelm, W.W., Weiss, A. and Hays, C.J., (2004). Putting genes into genetic coefficients. Field Crops Research, 90(1): 133-143.

Botwright, T.L., Condon, A.G., Rebetzke, G.J. and Richards, R.A., (2002). Field evaluation of early vigour for genetic improvement of grain yield in wheat. Australian Journal of Agricultural Research, 53(10): 1137-1145.

Campolongo, F., Tarantola, S. and Saltelli, A., (1999). Tackling quantitatively large dimensionality problems. Computer Physics Communications, 117(1-2): 75-85.

Day, W., Lawlor, D.W. and Day, A.T., (1987). The Effect of Drought on Barley Yield and Water-Use in 2 Contrasting Years. Irrigation Science, 8(2): 115-130.

Day, W. et al., (1978). Drought Experiment Using Mobile Shelters - Effect of Drought on Barley Yield, Water-Use and Nutrient-Uptake. Journal of Agricultural Science, 91: 599-623.

Farre, I. and Faci, J.M., (2006). Comparative response of maize (Zea mays L.) and sorghum (Sorghum bicolor L. Moench) to deficit irrigation in a Mediterranean environment. Agricultural Water Management, 83(1-2): 135-143.

Hafsi, M., Pfeiffer, W.H. and Monneveux, P., (2003). Flag leaf senescence, carbon content and carbon isotope discrimination in durum wheat grown under semi-arid conditions. Cereal Research Communications, 31(1-2): 161-168.

Ishaq, M., Hassan, A., Saeed, M., Ibrahim, M. and Lal, R., (2001). Subsoil compaction effects on crops in Punjab, Pakistan I. Soil physical properties and crop yield. Soil & Tillage Research, 59(1-2): 57-65.

Kemanian, A.R., Stockle, C.O. and Huggins, D.R., 2005. Transpiration-use efficiency of barley. Agricultural and Forest Meteorology, 130(1-2): 1-11.

Khan, M.A., Abdullah, M. and Mehmood, A., (2004a). Planting Time and Year Effect on Dry Matter Accumulation in Wheat Grains. Journal of Agricultural Research, Pakistan, 42(2): 153-162.

Khan, M.A., Zulkiffal, M., Imran, M. and ur Rahman, A., (2004b). Evaluation of Planting Time and Seeding Rate in Wheat (Triticum Aestivum L.). Journal of Agricultural Research, Pakistan, 42(2): 163-169.

Latiri-Souki, K., Nortcliff, S. and Lawlor, D.W., (1998). Nitrogen fertilizer can increase dry matter, grain production and radiation and water use efficiencies for durum wheat under semi-arid conditions. European Journal of Agronomy, 9(1): 21-34.

Lawlor, D.W., Day, W., Johnston, A.E., Legg, B.J. and Parkinson, K.J., (1981). Growth of Spring Barley under Drought - Crop Development, Photosynthesis, Dry-Matter Accumulation and Nutrient Content. Journal of Agricultural Science, 96: 167-186.

Legg, B.J., Day, W., Lawlor, D.W. and Parkinson, K.J., (1979). Effects of Drought on Barley Growth - Models and Measurements Showing the Relative Importance of Leaf Area and Photosynthetic Rate. Journal of Agricultural Science, 92: 703-716.

Manderscheid, R., Burkart, S., Bramm, A. and Weigel, H.J., (2003). Effect of CO2 enrichment on growth and daily radiation use efficiency of wheat in relation to temperature and growth stage. European Journal of Agronomy, 19(3): 411-425.

Qureshi, K.N., Ahmad, N. and Richter, G.M., (2007). Calibration and evaluation of a crop growth model for winter wheat applied to climate scenarios in Pakistan. Agricultural and Forest Meteorology, in preparation.

Richter, G.M. et al., (2005a). Risk indicators for crop management in hilly terrain, Interdrought-II, Rome, Conference proceedings.
Richter, G.M. et al., (2005b). Simulated WUE for England and Southern Italy past and future - climate and terrain impacts. WUEMED Workshop Proceedings, Rome.
Richter, G.M., Rana, G., Ferrara, R.M., Ventrella, D., Acutis, M., Trevisiol, P., Mayr, Th., Baggeley, N, Morris, J., Holmes, A., Trawick, P., Dailey, A. G., Robbins, P., Simota, C., (2006). Stability and Mitigation of Arable Systems in Hilly Landscapes. EU-QLK-5-CT-2002-01313, Report to the European Commission, Brussels.
Richter, G.M., Semenov, M.A., (2005). Modelling impacts of climate change on wheat yields in England and Wales: assessing drought risks. Agricultural Systems, 84: 77-97.
Saltelli, A., Tarantola, S. and Campolongo, F., 2000. Sensitivity analysis as an ingredient of modeling. Statistical Science, 15(4): 377-395.
Saltelli, A., Tarantola, S., Campolongo, F. and Ratto, M., (2004). Sensitivity Analysis in practice. A Guide to Assessing Scientific Models. John Wiley & Sons, 216 pp.
Solomon, K.F. and Labuschagne, M.T., (2003). Variation in water use and transpiration efficiency among durum wheat genotypes grown under moisture stress and non-stress conditions. Journal of Agricultural Science, 141: 31-41.
Turner, N.C., (2004). Sustainable production of crops and pastures under drought in a Mediterranean environment. Annals of Applied Biology, 144(2): 139-147.
Van Oijen, M., Rougier, J. and Smith, R., (2005). Bayesian calibration of process-based forest models: bridging the gap between models and data. Tree Physiol, 25: 915-927.
Villalobos, F.J., Hall, A.J., Ritchie, J.T. and Orgaz, F., (1996). OILCROP-SUN: A development, growth, and yield model of the sunflower crop. Agronomy Journal, 88(3): 403-415.