EVALUATION OF DIFFERENT CROP MODELS FOR ESTIMATING THE POTENTIALS TO INCREASE THE WATER USE EFFICIENCY UNDER CLIMATE VARIABILITY

ÉVALUATION DES MODELES DE CULTURES DIFFERENTES POUR ESTIMER LE POTENTIEL D'AUGMENTER L'EFFICACITE D'UTILISATION DE L'EAU EN VERTU DE LA VARIABILITE DU CLIMAT

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ABSTRACT

The interest in techniques to improve water use efficiency (WUE) such as controlled deficit irrigation is rising due to the emergence of strong competition for fresh water in order to comply with the increased demand for food worldwide. Additionally, the use of crop models in conjunction with complex decision support systems becomes more and more widespread making it essential to reliably predict WUE as ratio of water consumption and yield. The objective of this paper is the assessment of the problems that occur when certain crop models are applied to maximize the WUE. The crop models FAO-33, DAISY, and APSIM were used to calculate the risk in yield reduction in view of different sources of uncertainty, such as climate, while a stochastic framework for decision support for the planning of water supply in irrigation was employed. The stochastic framework consists of: (i) a weather generator for simulating regional impacts of climate change; (ii) a new tailor-made evolutionary optimization algorithm for optimal irrigation scheduling with limited water supply; and (iii) the above mentioned models for simulating water transport and crop growth in a sound manner. The results present stochastic crop water production functions (SCWPF) for different crops which can be used as basic tool to assess the impact of climate variability on the risk for the potential yield. Case studies from India, Oman, Malawi, and France are provided to evaluate the differences in modeling water stress and yield response for the different crop models.

RESUME

L'intérêt en techniques pour améliorer l'efficacité d'utilisation de l'eau (EUE) tels que l'irrigation déficitaire controlée s'est intensifié en raison de l'émergence d'une forte concurrence pour l'eau douce afin de se conformer à la demande accrue de nourriture dans le monde. En outre, l'utilisation de modèles de culture en combinaison avec des systèmes complexes d' aide-décision devient de plus en plus répandue ce qui rend indispensable la prédiction de WUE de manière fiable en tant que rapport

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entre la consommation d'eau et le rendement. L'objectif de ce document est l'évaluation des problèmes qui surviennent lorsque certains modèles de culture sont appliqués pour maximiser la WUE. Les modèles de culture de la FAO-33, DAISY et APSIM ont été utilisé pour calculer le risque de baisse de rendement, compte tenu des différentes sources d'incertitude, tel le climat, tandis qu’ un cadre stochastique d’ aide - décision a été employé pour la planification de l'approvisionnement en eau pour l'irrigation. Le cadre stochastique se compose : (i) du générateur de temps pour simuler les impacts régionaux du changement climatique; (ii) un nouvel algorithme de mesure de l'évolution d'optimisation, spécialement conçu pour la planification de l'irrigation optimale l'approvisionnement en eau limitée, et (iii) les modèles ci-dessus mentionnés pour simuler de façon valable le transport de l'eau et la croissance des cultures.. Les résultats présentent des fonctions stochastiques pour la production en eau des cultures (SCWPF) pour différentes cultures qui peuvent être utilisées comme outil de base pour évaluer l'impact de la variabilité climatique sur le risque pour le rendement potentiel. Des exemples faire en Inde, Oman, le Malawi et la France sont fournies afin d'évaluer les différences de stress hydrique de modélisation et la réponse respective de rendement pour les modèles de cultures différentes.

INTRODUCTION

Rising competition for fresh water to meet food requirements worldwide has grown into a renewed interest in techniques to improve water use efficiency (WUE) such as deficit irrigation. Additionally, while the application of crop models in conjunction with complex decision support systems becomes feasible, it is even more important to reliably predict WUE. Future objectives are therefore the reliable estimation of prospective water demand as well as minimum water demand for highest WUE. Climate change studies under water stressed conditions for different locations were carried out and their results for predicting future water demand for different crops were analyzed and evaluated. Along these lines the determination of requirements for a model to reliably estimate the WUE under climate change and climate variability by a stochastic framework was one objective of this paper. As a result certain prerequisites, which the models have to meet, were found in order to be qualified for such a kind of uncertainty analysis: (i) the model’s eligibility to cope with climate change and climate variability, (ii) the models parameter transferability in space and time, (iii) the practical aspect of being capable of batch processing (e.g. Monte Carlo, Optimization), and (iv) the model’s capability of taking water stress realistically into account.

MATERIALS AND METHODS

The evaluation of model requirements for different crop models is based on their application within a stochastic framework of a new planning tool for Optimal Climate Change Adaption Strategies for Irrigation – OCCASION (Schütze & Schmitz, 2010). This framework consists of: (i) a weather generator for simulating regional climate change impacts, (ii) a Global Evolutionary Technique for Optimal Irrigation Scheduling (GET-OPTIS), and (iii) the crop model itself (see Figure 1).The planning tool is applied to create stochastic crop water production functions (SCWPF) using an appropriate model for an arbitrary site investigated which are evaluated according to certain aspects such as plausibility in the face of climate change. This also involves the four prerequisite criteria mentioned above.

The weather generator LARS-WG is described in detail by Semenov et al. (1998). It creates daily synthetic statistically equal weather data of arbitrary length of global radiation, minimum and maximum temperatures, and precipitation from historical climate series. It also accounts for IPCC climate scenarios.

The optimization algorithm for optimal irrigation scheduling is explained in detail in Schmitz et al. (2007) and results in the maximum crop yield that can be achieved by a given but limited amount of water per growing season and where the quantity of each irrigation event is to be determined. The impact of an irrigation schedule is calculated by the crop model.

Four SVAT models namely DAISY (Abrahamsen & Hansen, 2000), CROPWAT (Smith, 1992), PILOTE (Mailhol et al., 1997), and Agricultural Production Model APSIM (Keating et al., 2003) for different locations were investigated in the context of OCCASION and the resulting SCWPF evaluated.

SCWPF are derived in three loops (see Figure 1). The objective of the first loop is to maximize yield under a certain climate condition for a preset amount of irrigation water during one growing cycle. With the second loop, a complete crop water production function (CWPF) representing the maximum yield that can be achieved with a limited amount of water is calculated by iterating through a range of irrigation water amounts. This is referred to as potential CWPF. In the third loop, the required amounts of CWPF are generated for deriving accurate statistical characteristics in a non-parametric way whereby the weather generator can be interpreted as a Monte Carlo sampler that provides the necessary climate series. The result is the SCWPF represented by an empirical probability function.

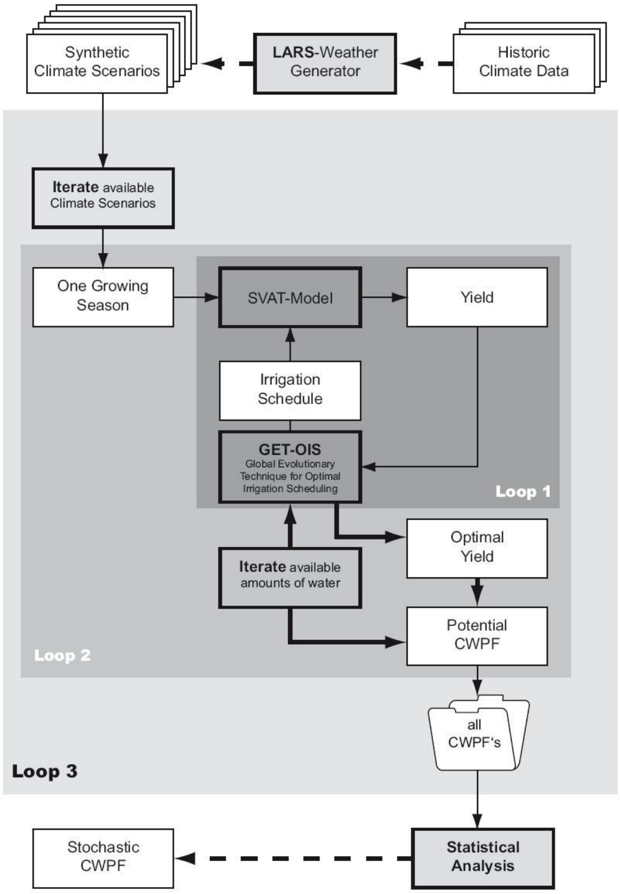

Figure 1. The framework OCCASION for generating stochastic crop water production functions (Schütze & Schmitz, 2010)

Figure 1. Le cadre OCCASION pour générer des fonctions stochastiques de production en eau des cultures (Schütze & Schmitz, 2010)

INVESTIGATED SITES

Montpellier, France

The first analysis presented investigates the application of the DAISY model for silage maize (variety Pioneer) that was cultivated on a loamy soil at the experimental site Lavalette in Montpellier, France. In this Mediterranean climate with 750mm of average annual rainfall, daily weather data for 17 years (1991 to 2007) was utilized and 500 realizations of synthetic weather data generated by LARS-WG. A subset that covered the growing period from 1st May to 13th October was then selected and applied for optimizations runs with DAISY. Crop growth parameters provided by the model and which are tested in many environments (Abrahamsen & Hansen, 2000) were applied whereby initial water stress was set to zero. The crop was subject to different irrigation schemes generally including always at least on full irrigated and one rain fed treatment.

The model was successfully parameterized and verified by field experiments where crop parameters were identified as reliable. By application of the 500 climate series SCWPF were obtained and analyzed with descriptive statistical methods such as quantiles, median, and statistical moments. The result of this analysis is shown in Figure 2 where no rainfall was considered. In there, the variations in maize yields reach up to 3t/ha whereby increasing significantly with additional amount of water applied. The upper part of the SCWPF is the most important one. The impact of climate variability on potential yield is obvious caused by the variability of global radiation. This can be explained by the nearly normally distributed yield at full irrigation (not shown). The crop simulated with DAISY shows realistic behavior for light deficit irrigation whereas for no or little water unrealistic behavior can be observed since photosynthesis is reduced but no signs of irreversible damage due to drought stress occurs. Once fully irrigated again, the crop falls back to full transpiration.

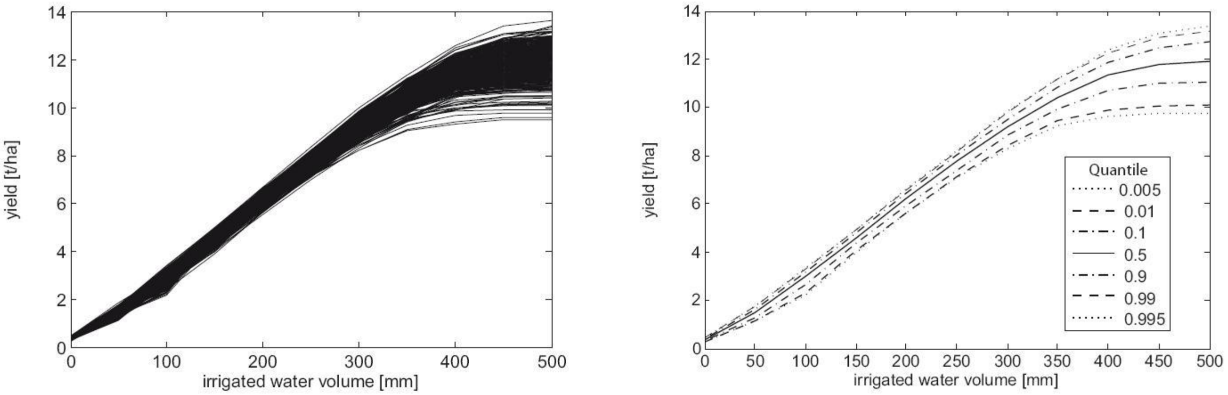

Figure 2. Samples of generated CWPFs (left) and SCWPF (right) under no rain conditions for maize grown at Lavalette site (Montpellier, France)

Figure 2. Des échantillons de CWPFs générés (à gauche) et SCWPF (à droite) dans des conditions de non pluie pour le maïs cultivé sur le site de Lavalette (Montpellier, France)

In a next step, the variability of rainfall was added to the simulation by taking precipitation into account. The result in Figure 3 shows 500 simulations where the yield variability is clearly dominated by rainfall without irrigation. The span of yield ranges from 0.5t/ha to 7t/ha. As soon as irrigation water is applied, global radiation becomes more and more important up to a point where it almost entirely governs the variability of yield. Comparison to the SCWPF without rainfall reveals slight decreases in the quantile values which cannot be compensated thus a small impact of rainfall variability remains.

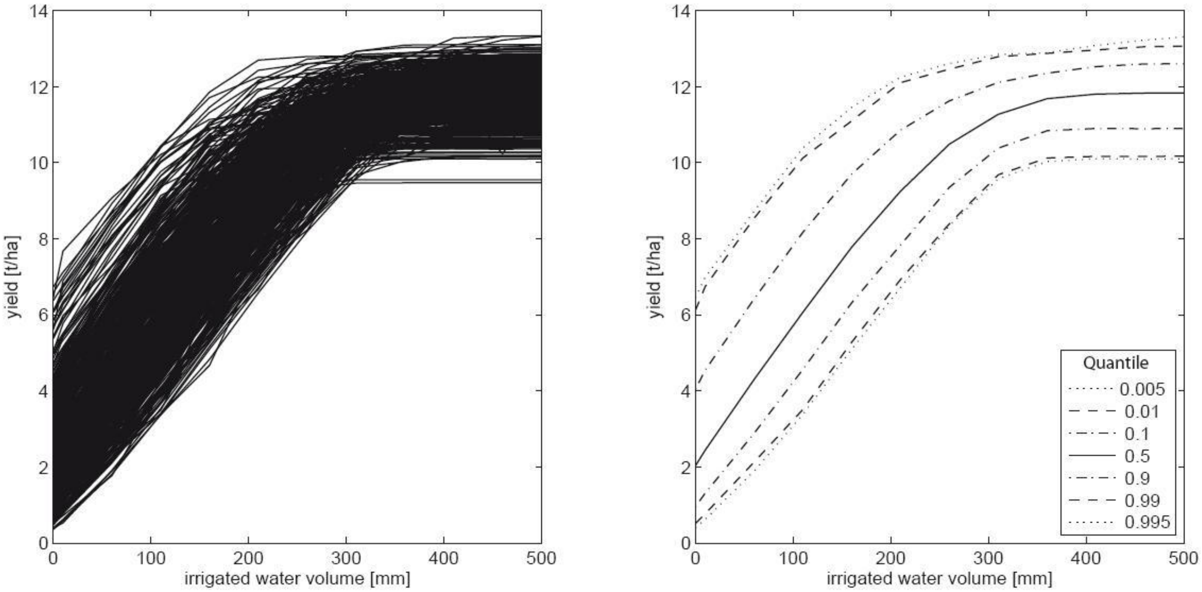

Figure 3. Samples of generated CWPFs (left) and SCWPF (right) under rain conditions for maize grown at Lavalette site (Montpellier, France)

Figure 3. Des échantillons de CWPFs générés (à gauche) et SCWPF (à droite) dans des conditions de pluie pour le maïs cultivé sur le site de Lavalette (Montpellier, France)

Finally, a SCWPF was generated in the face of climate change by application of the IPCC-A2 scenario. The results for 500 CWPFs are shown in Figure 4 where a notable drop in yields of around 2t/ha compared to baseline scenario can be found. Additionally, for no or low irrigation a skewed distribution can be observed (not shown) due to the significant impact of rainfall variability. The skewness coefficient is higher in A2 scenario due to higher probability of dry conditions. The highest variance in potential yield can be observed between 60mm and 210mm due to the superposition of rainfall and radiation variability. There is also a change in the type of distribution from skewed to symmetrically distributed with additional water supply which confirms the domination of radiation variability. The highest crop water use efficiency seems to be at 310mm.

The results from no rain, rain influenced, and climate change scenarios show that DAISY can be used in the context of OCCASION to forecast the impact of climate variability for historical and future climate scenarios on potential yields since the SCWPFs resulted in good agreement with the expected outcome. DAISY can therefore serve as a reference model for the three other models presented in this study.

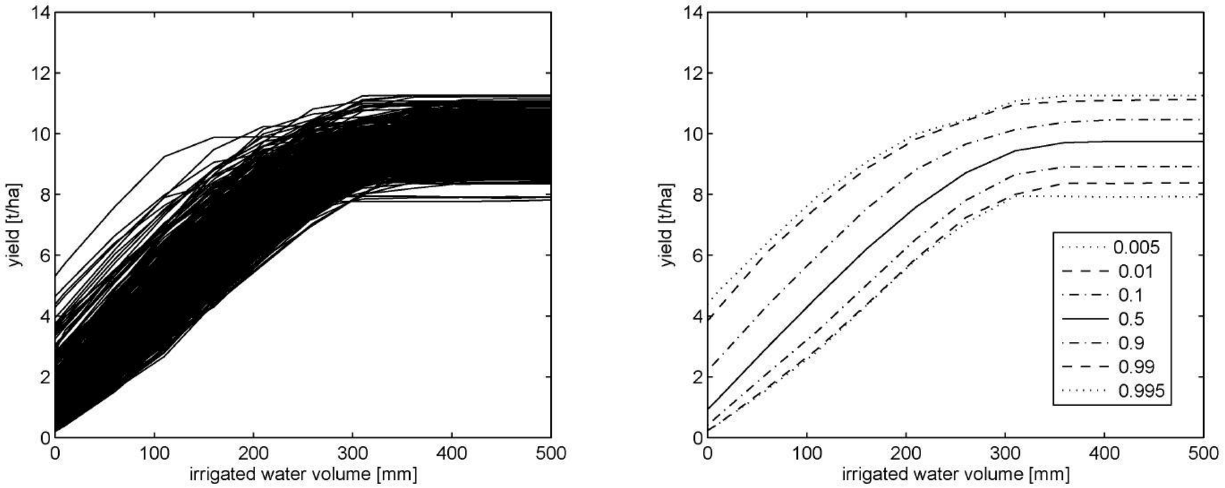

Figure 4. Samples of generated CWPFs (left) and SCWPF (right) under rain conditions in IPCC-A2-scenario

Figure 4. Des échantillons de CWPFs générés (à gauche) et SCWPF (à droite) dans des conditions de pluie en GIEC-A2-scénario.

Kharagpur, India

The next model investigated is CROPWAT, a model developed and provided by the Land and Water Division of the FAO and well known to farmers for easy estimation of crop water demand. CROPWAT is based on the FAO papers 56 and 33 and, for the latter, its fundamental equation where the relative loss in yield is proportional to the relative reduction in evapotranspiration described by Jensen (1968).

The simulations were conducted with observed meteorological data from Kharagpur, India, for 16 years (1991 to 2007), consisting of rainfall, evaporation, relative humidity, maximum and minimum temperatures, wind speed, and solar radiation. The climate in Kharagpur is sub-humid to tropical with a growing season from September to March. Maize and wheat were investigated whereby evapotranspiration rates were calculated using Penman-Monteith equation and crop coefficients for the investigated crops.

The LARS-WG weather generator was used for generating a number of statistically identical but similar weather scenarios. These scenarios resulted in the creation of CWPFs which were statistically evaluated. The resulting SCWPF for maize and wheat are shown in Figure 5 where the relative yield is plotted against the irrigation volume with the quantiles of 10%, 50%, and 90% (from top to bottom).

For both crops, full irrigation is reached at around 600mm of irrigation water. For no or low irrigation, the span in relative yield is notably high with around 0.6 and decreases with additional supply of irrigation water. For full irrigation, another extreme can be observed; the differences in quantiles are equal zero. This can be explained by the models incapability to account for temperature and global radiation variability caused by the yield response proportional factor. This factor does not substitute for photosynthesis processes; CROPWAT is therefore not suitable for determining the impact of potential yield by OCCASION.

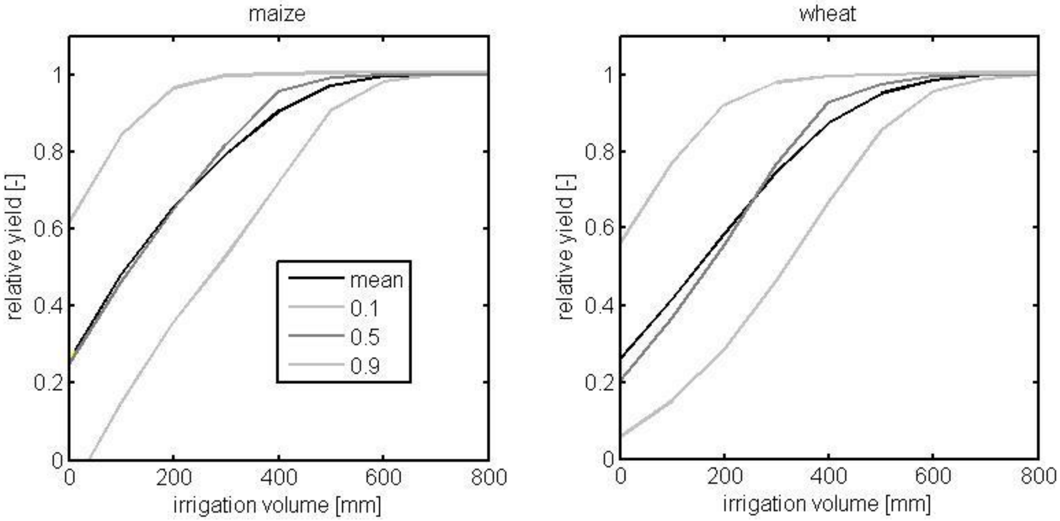

Figure 5. SCWPFs and their empirical quantiles 0.1, 0.5, and 0.9 from top to bottom respectively for maize and wheat at Kharagpur, India

Figure 5. SCWPFs et leurs quantiles empiriques 0,1, 0,5 et 0,9 de haut en bas, respectivement, pour le maïs et le blé à Kharagpur, Inde.

Bwanje Valley, Malawi

In this research work, maize along with observed meteorological climate data (1972 to 2006), soil characteristics (sandy loam), and a irrigation management plan from the Bwanje irrigation scheme, a site in Bwanje Valley, Malawi, was investigated and the PILOTE model utilized.

PILOTE (Smith, 1992) is an operative crop model for predicting the yield by simulating the soil water balance and the leaf are index at a daily time step. Water is generally assumed to be the only limiting factor when nitrogen applications meet plant requirements. Further model descriptions and applications can be found in Mailhol et al., (1997) and Khaledian et al., (2009).

The Bwanje irrigation scheme was introduced to farmers after droughts led to famines among rural people in Malawi. The scheme covers an area of 800ha. Again, the LARS weather generator provided synthetic but statistically similar weather scenarios for the tropical continental climate and in addition future climate change scenarios suggested by the IPCC, namely A2 and B1 for the year 2080, were applied. A total of 400 realizations for each scenario were created and CWPFs were calculated. The statistical analysis of these functions resulted in the SCWPF for baseline, B1, and A2 climate scenarios. The results are shown in Figure 6.

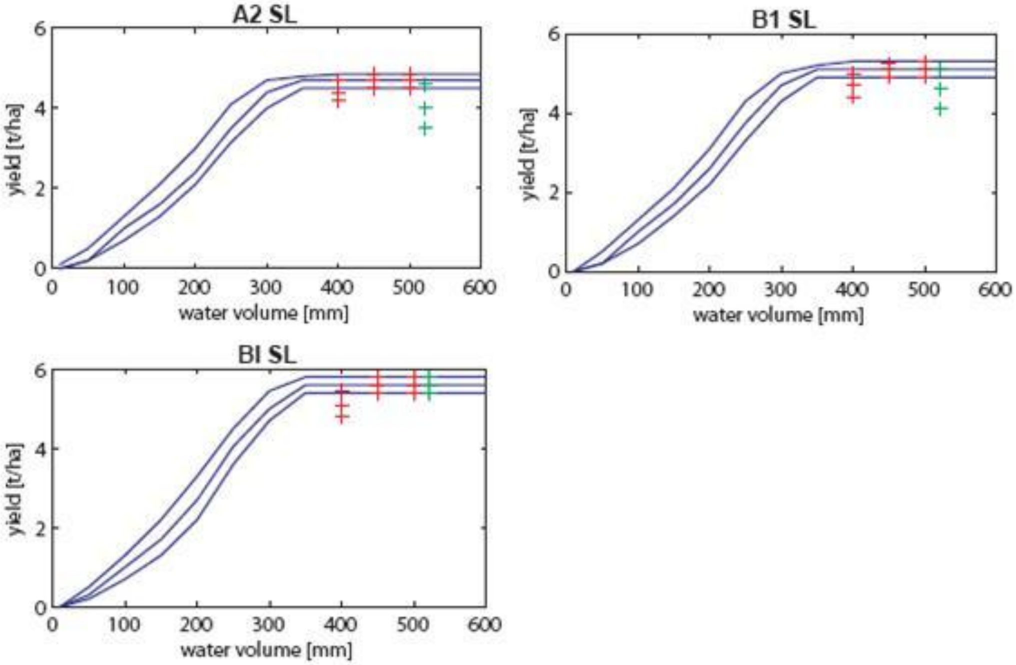

Figure 6. SCWPFs and their empirical quantiles 0.1, 0.5, and 0.9 respectively for maize for IPCC scenarios A2, B1, and baseline (Bl), with traditional irrigation scheme (green asterisk) and a season independent irrigation schedule (red asterisk)

Figure 6. SCWPFs et leurs quantiles empiriques 0,1, 0,5 et 0,9, respectivement, pour le maïs GIEC scénarios A2, B1, et référence (Bl), avec système d'irrigation traditionnel (astérisque vert) et une saison d'irrigation indépendant2 (rouge astérisque).

As Figure 6 shows, there is a certain degree of variability within the quantiles once full irrigation is reached. The comparison of the two future climate scenarios B1 and A2 reveal a reduction in yields due to changes in temperature. The results in detail show that by using the optimization algorithm the potential maximum yield is achieved at 350mm irrigation volume for the baseline scenario. Compared with the traditional irrigation scheme (green asterisk) where 522mm at a four days fixed irrigation frequency interval were applied, water savings of 33% (=172mm) can be achieved. Applying the current irrigation scheme for B1 and A2 scenarios in contrast would result in heavy impacts on yields and is therefore not sustainable for future climate scenarios. The model was also capable of finding solutions for 400mm, 450mm, and 500mm of total irrigation water for a season independent irrigation schedule based on all realizations indicated by the red asterisks. Up to this point, PILOTE seemed suitable for OCCASION.

In a next step, maize crop parameters were taken and utilized for a site in Montpellier, France, where field experiments were carried out. A model was parameterized and a plot of maize treated according to predictions for an irrigation schedule generated by PILOTE. This resulted in yields of 12t/ha whereas the model predicted 14t/ha. The development of the LAI did also not match. A closer investigation revealed unstable crop parameters and led to the conclusion of their non-transferability to other locations. Additionally, variations in the crop parameters themselves between different growing seasons at the same location render PILOTE rather difficult to apply with OCCASION. However, reliable results may be obtained once stable crop parameters are found.

Al-Batinah, Oman

The last model presented is the Agricultural Production System Simulator APSIM. The modular framework of APSIM provides different plant, soil, and management modules and was developed by the Agricultural Production Systems Research Unit in Australia (Keating et al., 2003) to simulate biophysical processes in farming systems.

Maize (variety Katumani) and sorghum grown and irrigated at a hypothetical site in the coastal plain of the Al-Batinah, Oman, were investigated. Observed weather data for 18 years (1991 to 2006) from Seeb weather station were used and baseline scenarios as well as IPCC scenarios B1 and A2 for the year 2080 applied. 500 realizations for each climate scenario were calculated whereas as subset of 100 realizations was selected for simulation/optimization runs in APSIM. An exemplary loamy soil from the APSIM soil database was selected which had similar properties to soils in the region; selected crop management practices such as sowing density resembled practices in the region. Sowing date was set to 15th January with no initial water deficit present. Fertilizer was only applied when nutrient stress was imminent.

The resulting SCWPF for maize and sorghum evaluated by descriptive statistical analysis are shown in Figure 7 and Figure 8 respectively. Both figures represent the impact on potential yield for one growing cycle for baseline, B1 and A2 scenarios. At an irrigation volume of 150mm (middle row) mainly precipitation, radiation, and temperature govern the yield. At around 400mm for maize and 450mm for sorghum, no further application of water results in increased crop yields. The remaining variation in yields is due to variations in temperature and radiation. Comparing all three climate scenarios, yield for maize is significantly reduced (up to 1.5t/ha for 2080). This can be explained by the temperature and radiation impact on plants in the early growing stages which lead to faster plant development and a shorter vegetative phase. At the same time, standard deviations decrease with available amount of water as well as with temperature meaning the reliability to reach a certain crop yield increases.

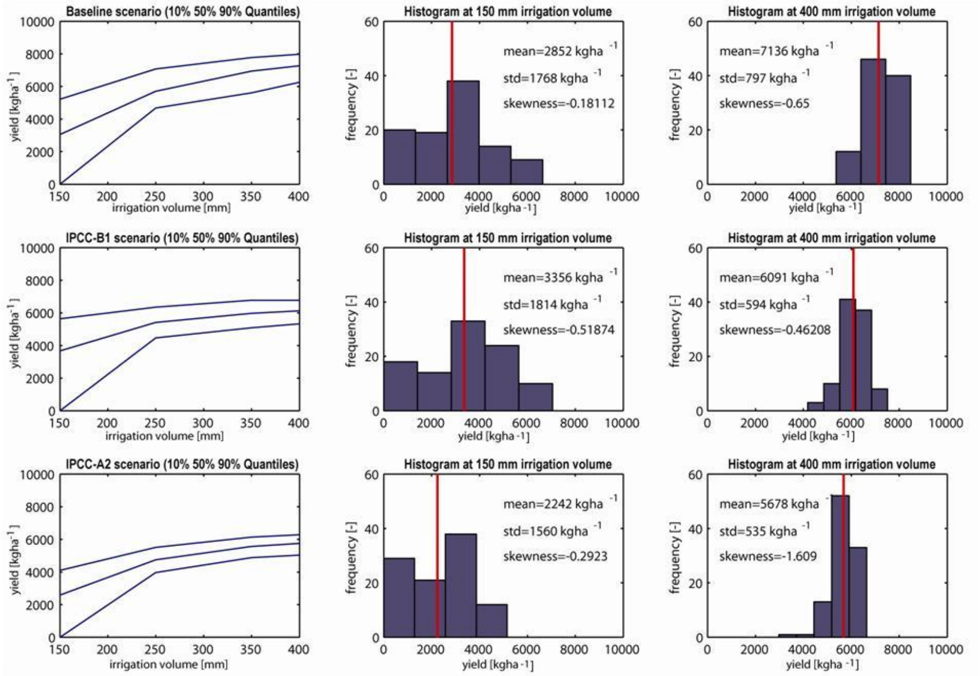

Figure 7. SCWPFs for maize for baseline, IPCC-B1, and A2 scenarios for 150mm and 400mm irrigation volume at Al-Batinah site, Oman

Figure 7. SCWPFs pour le maïs de base, le GIEC-B1, et les scénarios A2 pour 150mm et 400mm volume d'irrigation sur le site Al-Batinah, Oman

The decrease in yields for sorghum for the future climate scenarios is not as dramatic as for maize indicting a lighter impact of water stress and climate variability. There are lower differences in mean potential yields at full irrigation (0.6t/ha) for the expected future climate condition in 2080 as well as a change in yield distributions between 150mm and 450mm from skewed to normal indicating dominating impacts of temperature and radiation.

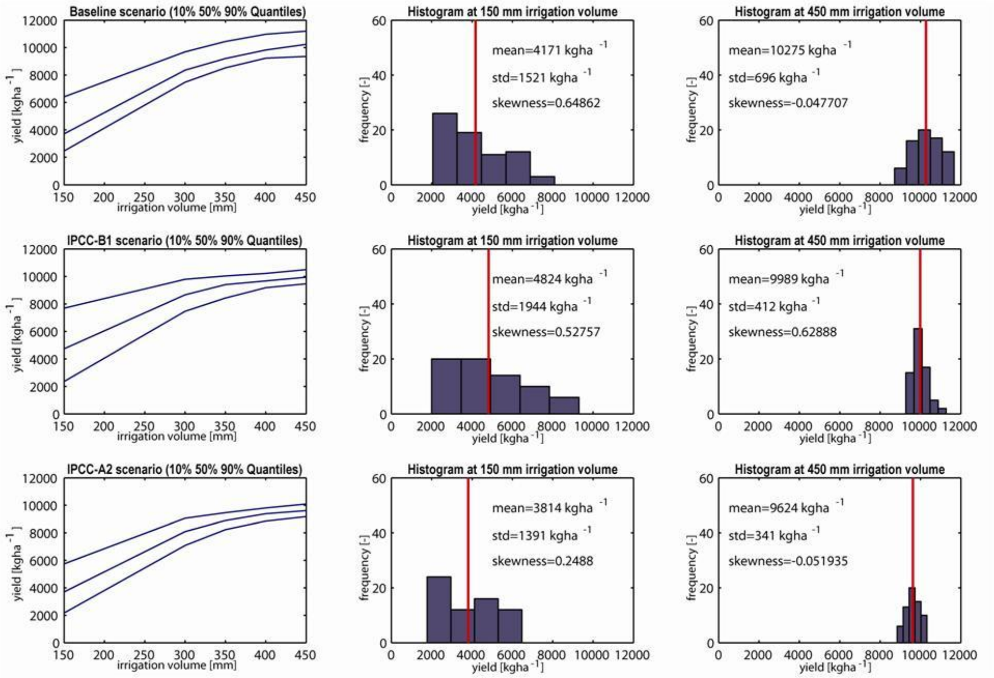

Figure 8. SCWPFs for sorghum for baseline, IPCC-B1, and A2 scenarios for 150mm and 400mm irrigation volume at Al-Batinah site, Oman

Figure 8. SCWPFs pour le sorgho pour référence, GIEC-B1, et les scénarios A2 pour 150mm et 400mm volume d'irrigation sur le site Al-Batinah, Oman

It can be concluded that even though no model verification by field experiments have been carried out yet, results show that APSIM generates realistic values and is therefore promising for investigating the development of potential yields for different crops under climate variability.

SUMMARY AND CONCLUSION

In this paper, four SVAT models, namely CROPWAT and PILOTE (both empirical models with water balance modules) as well as DAISY and APSIM (physiological crop growth models with water transport modules which are important for modern irrigation systems) were investigated for their suitability to be applied in the stochastic framework OCCASION. The stochastic framework consists of a weather generator for providing site specific climate scenarios, a problem specific algorithm for optimal irrigation scheduling, and a SVAT model for investigating the potential yield for different crops under climate variability by evaluating stochastic crop water production functions.

Besides the unrealistic behavior of full photosynthesis capabilities for crop after drought stress occurred, the model DAISY showed realistic results for maize under no rain, rain, and climate change conditions. DAISY was therefore used as a role model to whom the other three crop models were compared to. CROPWAT proved to be unsuitable for the intended task since the yield response proportional factor, which accounts for the relative loss in yield, is not adequate to describe plant physiology and therefore the plant's reaction to climate variability and climate change especially for full irrigation. PILOTE did perform well and realistic results were obtained for the investigated site but the model is in need for stable crop parameters which have to be derived over several growing periods in order to be applicable unconditionally. APSIM seems promising since results are realistic but have yet to be verified in field experiments.

The study above shows that not all types of models are qualified and certain requirements have to be met for a successful and reliable application. Requirements in this context are a good representation of plant physiology (e.g. assimilation, respiration, partitioning of carbon) and the realistic representation of crop's response to water stress. Additionally, the spatial distribution for modeling soil moisture (when considering micro irrigation) has to be adequate as well as a temporal resolution of days instead of weeks for a realistic description of water transport and evaporation. Finally, all the models are in need for robust parameters which allows the transfer of crop parameters from one investigation site to another.

RÉSUMÉ ET CONCLUSION

Dans cet article, quatre modèles SVAT, à savoir CROPWAT et Pilote (les deux modèles empiriques avec des modules de l'équilibre de l'eau) ainsi que DAISY et APSIM (physiologiques modèles de croissance des cultures avec des modules de transport par eau qui sont importantes pour les systèmes modernes d'irrigation) ont été étudiés pour leur aptitude à être appliquées à l'occasion cadre stochastique. Le cadre stochastique se compose d'un générateur de temps pour fournir des scénarios climatiques spécifiques du site, un algorithme de problème particulier pour la planification de l'irrigation optimale, et un modèle SVAT pour enquêter sur le rendement potentiel des cultures différentes en vertu de la variabilité du climat en évaluant stochastique en eau des cultures de production.

Outre le comportement réaliste des capacités de la photosynthèse totale pour les cultures à la sécheresse après eu lieu, le modèle a montré DAISY résultats réalistes pour le maïs en aucun pluie, la pluie, et les conditions de changement climatique. DAISY est donc utilisé comme un modèle auquel les trois autres modèles de cultures ont été comparées à. CROPWAT s'est avéré inadapté à la tâche depuis destinés facteur de la réponse rendement proportionnel, ce qui explique la relative perte de rendement, n'est pas suffisant pour décrire la physiologie des plantes et donc la réaction de la plante à la variabilité du climat et le changement climatique en particulier pour l'irrigation complète. PILOTE ne performants et réalistes résultats ont été obtenus pour le site étudié, mais le modèle est dans le besoin pour les paramètres de culture stable qui doivent être tirés au cours de plusieurs périodes de croissance afin d'être applicable sans condition. APSIM semble prometteur puisque les résultats sont réalistes, mais n'ont pas encore été vérifiée dans les expériences de terrain.

L'étude ci-dessus montre que tous les types de modèles sont qualifiés ainsi que certaines exigences doivent être remplies pour une application réussie et fiable. Les besoins dans ce contexte sont une bonne représentation de la physiologie des plantes (par exemple, l'assimilation, la respiration, le stress de partitionnement de carbone) et la représentation réaliste de la réaction des cultures à l'eau. En outre, la répartition spatiale de l'humidité du sol de modélisation (lors de l'examen micro-irrigation) doit être adéquate ainsi que d'une résolution temporelle de quelques jours au lieu des semaines pour obtenir une description réaliste de transport de l'eau et l'évaporation. Enfin, tous les modèles sont dans le besoin pour les paramètres robuste qui permet le transfert de paramètres de cultures d'un site d'enquête à l'autre.

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