EVALUATION OF SIMULATION BASED DEFICIT IRRIGATION AND FERTILIZATION STRATEGIES TO MAXIMIZE WATER PRODUCTIVITY AND NITROGEN USE EFFICIENCY

EVALUATION DES STRATEGIES D'IRRIGATION DEFICITAIRE ET DE FERTILISATION UTILISANT LA SIMULATION POUR AUGMENTER LA PRODUCTIVITE DE L'EAU ET LA EFFICIENCE D'UTILISATION D'AZOTE

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ABSTRACT

A doubling in global food demand projected for the next 50 years poses huge challenges for the sustainability of crop production. Moreover, society is becoming increasingly concerned with agricultural use of water and nitrogen which are two critical resources for crop growth. Avoiding excessive percolation and adjusting N-applications are prerequisites to reduce N-leaching while maintaining high crop yields. For that, Soil-Vegetation-Atmosphere Transfer (SVAT) models, which describe physical and physiological processes of crop growth as well as of water and matter transport, enhance optimal irrigation and fertilization management. In this study, a new simulation based optimization framework for simultaneous scheduling of irrigation and N-fertilization was developed in order to maximize water productivity (WP) and at the same time nitrogen use efficiency (NUE). The employed framework consists of a tailor-made evolutionary optimization algorithm and the process-based SVAT-model DAISY for simulating water balance, nitrogen balance and crop growth. The optimization framework for optimizing irrigation and N-fertilization was applied in experiments in 2010, were corn (Zea mays L.) was cultivated in a vegetation hall. Irrigation water and nitrogen were simultaneously and optimally distributed over one growing period to achieve maximum WP and NUE. The simultaneous scheduling strategy was compared to different other deficit irrigation and deficit N-fertilization strategies. The results showed that applying the framework, WP was increased

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up to 3.6 kg m^{-3} and NUE up to 58 kg kg^{-1}, respectively. It can be concluded that simulation based optimization of irrigation and N-fertilization is capable to elevate WP and NUE.

Key words: *Deficit irrigation, Simulation, Water productivity. Nitrogen use efficiency, Corn.*

RESUME ET CONCLUSIONS

Il y a une inquiétude croissante concernant l' utilisation excessive d'eau et d'azote dans l'agriculture, en raison de la diminution de l'efficacité des ressources utilisées et de la pollution de l'eau souterraine. Eviter la percolation excessive et ajuster l'application de N sont un pré-requis pour diminuer le lessivage de N en maintenant un bon rendement. Une telle gestion nécessite une bonne connaissance de la dynamique de N dans le sol et des besoins en eau et en azote de la plante. La simulation avec des modèles peut capturer les interactions et peut être considérée comme un instrument puissant pour assister l'optimisation de l'irrigation et de la fertilisation.

Dans cette recherche, un outil de travail utilisé pour l'optimisation de l'horaire d'irrigation et de fertilisation, basé sur un modèle de simulation nommé OCCASION a été appliqué afin de comparer les différentes stratégies d'irrigation et de fertilisation déficitaires. L'outil de travail utilisé consiste en un algorithme d'optimisation évolutionniste GET-OPTIS et le modèle SVAT (anglais: Soil-Vegetation-Atmosphere Transfer) DAISY pour simuler la balance d'eau, la balance d'azote et la croissance des cultures. En 2010 on a conduit une expérience pour laquelle on a cultivé du maïs dans une serre. L'irrigation et la fertilisation par N ont été distribuées simultanément et de manière optimale pendant la période de croissance pour atteindre une productivité d'eau (WP) et une efficacité de l'utilisation d'azote (NUE) maximales. On a déterminé trois horaires d'irrigation défizitaire en optimisant la quantité d'eau irriguée (60% dírrigation complète), un seuil de force de succion du sol constant pendant la période de croissance, et des seuils de force de succion du sol adaptés à la période de croissance. En outre, un traitement d'irrigation complète avec un seuil de tension du sol constant pendant la période de croissance a été réalisé. Avec deux traitements supplémentaires, on a optimisé la fertilisation par l'azote, avec pour résultat un traitement limité en eau et en azote conjugué, et un traitement limité en azote mais irrigué complète.

Les résultats montrent que l'application de OCCASION a été utilisée avec succès pour obtenir une WP élevée. Avec les traitements optimisés, WP a été augmentée de 25% comparé au traitement irrigué complètement. NUE a été maximale dans le traitement limité en azote mais irrigué complètement (58 kg grain kg N^{-1}). En conclusion, l'optimisation basée sur des simulations de l'irrigation ou de la fertilisation par l'azote a permis d'augmenter WP et NUE. Pourtant il reste des problèmes avec l'optimization d'eau et d'azote conjugué.

Mots clés : *Irrigation déficitaire, simulation, productivité de l'eau. efficience d'utilisation d'azote, maïs.*

(Traduction française telle que fournie par les auteurs)

1. MATERIALS AND METHODS

1.1 Experimental setup

In 2010, experiments with corn (*Zea mays L*., variety PR36K67) were conducted in the vegetation hall of the Dürnast Experiment Station of the Technische Universität München, Germany (48°24'N, 11°41'E; 473 m altitude). On 14/05/2010, five seeds per container were sown into 18 containers (0.95 m x 0.55 m x 0.73 m, without drainage). The three containers of each of the six treatments were placed into three rows, leading to row distances of 75 cm and a seeding density of 6.7 plants per m2. The used soil was loamy sand (79.2% sand, 17.5% silt, and 3.3% clay). Adequate amounts of P and K-fertilizers were applied at sowing. The drip irrigation system NMC-pro (Netafim) was used. Five emitters per container were installed, one next to each plant, resulting in a discharge rate of 8.5 mm h^{-1}. In one of three containers per treatment, four TDR probes and four pF-Meters at four different heights (-20, -30, -40 and -60 cm soil depth) were installed (one TDR probe and one pF-Meter next to each other are referred to as sensor pair). The pF-Meters at -30 cm soil depth served for irrigation control. In each of the other two containers, only one sensor pair was installed at -30 cm soil depth. Soil tensions and soil water contents were measured by pF-Meters and TDR probes every 10 minutes, respectively.

A meteorological station was installed to provide 10 min data. The roof and side windows of the vegetation hall were opened whenever the sun was shining.

The chlorophyll present in the plant leaves and closely related to the nutrimental condition of the plant was measured using a Chlorophyll Meter named SPAD-Meter (Spectrum Technologies Inc.). After harvest (28/09/2010), grain yield at 15% humidity and total dry matter were determined. For further evaluations, water productivity (WP) in kg m^{-3} (grain yield divided by the total amount of applied water) and nitrogen use efficiency (NUE) in kg grain kg N^{-1} (grain yield divided by the total amount of applied N) were calculated.

1.2 Optimization framework for irrigation and N-fertilization scheduling

The new simulation based optimization framework for irrigation and N-fertilization scheduling OCCASION was applied in order to simultaneously and optimally distribute irrigation water and N over one growing period to achieve maximum WP and NUE. The framework consists of the tailor-made evolutionary optimization algorithm GET-OPTIS (Schütze et al., 2010) and the process-based SVAT-model DAISY (Hansen, 2002) for simulating water balance, nitrogen balance and crop growth (Fig.1). Moreover, the stochastic weather generator LARS-WG (Semenov and Barrow, 2002) was used to generate long time-series of 200 years which statistically resemble observed weather for the vegetation hall. The optimization framework consists of three loops. In the case of an optimization of the irrigation schedule, the resulting crop water production functions (CWPF) give the relation between yield and irrigation water applied. The CWPFs will be analyzed statistically, now called stochastic crop water production functions (SCWPF). In the case of a simultaneous optimization of the irrigation and N-fertilization schedule, crop water nitrogen production functions (CWNPF) and stochastic crop water nitrogen production functions (SCWNPF) are generated, respectively (Fig.1).

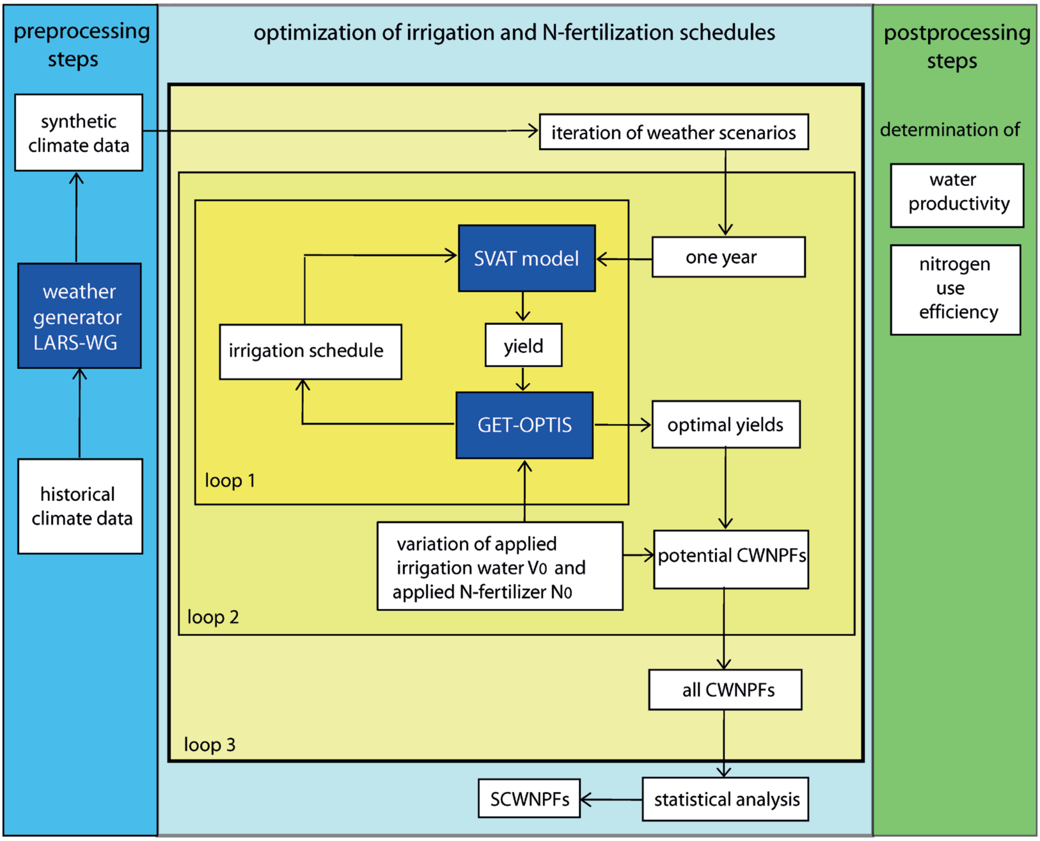

Figure 1. Scheme of the optimization framework to simultaneously and optimally distribute irrigation water and N over one growing period to achieve maximum WP and NUE (Schéma de l'outil de travail de l` optimisation d` irrigation et de fertilisation par N)

1.2.1 Irrigation and N-fertilization schedules

For determining the irrigation and N-fertilization schedules for corn, the tailor-made global optimization technique GET-OPTIS for optimal irrigation scheduling with limited water supply (Schütze et al., 2010) and the calibrated SVAT model DAISY (Hansen, 2002) were applied. The objective was to maximize WP (with a reliability of 90%) for all treatments and, in the case of T5 and T6, to maximize NUE simultaneously. In the case of T2 and T6, full irrigation was applied, aiming to fully irrigate but not over irrigate. In the case of T1-T4, full N-fertilization was applied, whereas for T5 and T6, a deficit N-fertilization schedule was determined aiming to maximize WP and NUE simultaneously.

Hence, three different deficit irrigation schedules and one deficit N schedule were determined leading to 6 treatments (T1-T6):

- T1: 60% of the irrigation amount of full irrigation (full N fertilization)
- T2: full irrigation and full N fertilization

- T3: a constant soil tension threshold throughout the growth period of the crop (full N fertilization)
- T4: optimizing a soil tension threshold that was adapted to four growth stages of the crop (full N fertilization)
- T5: 60% of the irrigation amount of full irrigation and simultaneously optimizing the N fertilization
- T6: full irrigation and optimizing the N fertilization

The four growth stages applied in T4 are based on FAO: Stage I lasts until 10 days before flowering (corresponding to developments stages DS 0-0.85 of SVAT model Daisy), stage II lasts from 10 days before flowering to 10 days after flowering (DS 0.85-1.15), stage III lasts from 10 days after flowering until 15 days before ripening (DS 1.15-1.75), and stage IV lasts from 15 days before ripening until ripening (DS 1.75-2.0).

Within the soil tension controlled treatments T2, T3, T4 and T6, the pF-Meters at -30 cm soil depth served for irrigation control. After each irrigation event, a redistribution time of 3 h was forced. For further explanations concerning the optimization of the irrigation schedule see (Kloss, 2011).

1.2.2 SVAT model DAISY

The SVAT model DAISY (Hansen, 2002) is a well-tested physically based 1D SVAT model for simulating water balance, heat balance, solute balance and crop production. It consists of the three main components bioclimate, vegetation and soil and requires site specific weather and management data, and vegetation and soil parameters. The water balance model comprises a surface and a soil water balance and includes water uptake by plants. Water flow in the unsaturated zone can take place as Darcy flow within the soil matrix or as gravity flow in distinct macropores. The matrix flow regime is described by the Richards equation. The growth period of the deterministic plant growth model is divided into three temperature and day length based development stages. The water stress model is based on the assumption that transpiration and CO_2 assimilation are governed by stomata responses, and that stomata are open when intercepted water is evaporated from the leaf surfaces. The solute balance model simulates transport, sorption and transformation processes with special emphasis put on nitrogen dynamics. In the case of plant parameters for that corn variety, calibration took place for another study using data from a field experiment in Southern France. The determined parameters were applied in that study.

1.2.3 Inverse calibration of soil parameters

The calibration of the soil parameters was done by inverse modeling applying the Covariance-Matrix-Adaption Evolution Strategy (CMA-ES). An estimation of the van Genuchten/Mualem parameters using soil tension and soil water content data of an infiltration event on 04/06 of all four soil depths (treatment T2) took place. For first estimations, soil parameters determined by ROSETTA (Schaap et. al, 2001) utilizing laboratory analysis results were applied.

2. RESULTS

2.1 Optimization results

The irrigation amounts per irrigation event and tension thresholds in the optimized irrigation schedules were:

- T1: 60% of the irrigation water of T2 were applied per irrigation event
- T2: Irrigation amounts of 7.2 mm at a threshold of -130 hPa were applied
- T3: Irrigation amounts of 6 mm at a tension of -1250 hPa were applied
- T4: Irrigation amounts of 6 mm at -1400 hPa (stage I), 2.9 mm at -150 hPa (stage II), 11.6 mm at -1250 hPa (stage III) and 2.2 mm at -1300 hPa (stage IV) were applied
- T5: The irrigation schedule is equal to the one of T1
- T6: The irrigation schedule is equal to the one of T2 (full irrigation)

For N scheduling, the optimized N deficit schedule was applied at T5 and T6, whereas T1-T4 were fully N fertilized. In total, the application in the case of the optimized deficit N-fertilization was about 60% of full N fertilization. For T1-T4, N-fertilization was applied on DAS 6 (63 kg N ha^{-1}), DAS 32 (63 kg N ha^{-1}), DAS 63 (45 kg N ha^{-1}) and DAS 97 (63 kg N ha^{-1}), leading to a total N-fertilization of 234 kg N ha^{-1}. For T5 and T6, N-fertilization was applied on DAS 6 (63 kg N ha^{-1}), DAS 63 (21 kg N ha^{-1}), and DAS 97 (63 kg N ha^{-1}), in total 147 kg N ha^{-1}. Due to soil probes in T2, N content before sowing and after harvest were about 20 and 1 kg N ha^{-1}, respectively. The resulting yields and irrigation and N-fertilization amounts for all treatments are shown in Table 2.

2.2 Soil parameter

The determined van Genuchten/Mualem parameters shown in Table 1 were used for further optimization runs.

Table 1. Van Genuchten/Mualem (vGM) parameters estimated with CMA-ES based on soil tension and water content data of the infiltration event on 04/06/2010 (Des parameters de van Genuchten/Mualem déterminés avec CMA-ES reposé sur des données de succion du sol et de teneur en eau d'un évent d'infiltration en 04/06/2010)

vGM parameter	θ_{res} [%]	θ_s [%]	α [cm^{-1}]	n [-]	K_s [cm d^{-1}]
Estimated value	3.52	39.05	0.05352	1.5725288	482.4

2.3 Yields, water productivities and nitrogen use efficiencies

As expected, grain yield was highest for fully irrigated T2 (irrigated with 398 mm including infiltration event), followed closely by T3 (irrigated with 289 mm) (Table 2). Comparing both tension controlled deficit irrigated treatments, T3 yielded much higher with a similar total irrigation amount compared to T4. Due to low irrigation amounts but also pests which mainly affected T1, grain yield of T1 was reduced (see also Fig.2). However, WP was highest for T3 (3.6 kg m^{-3}), followed by T1 and T4 (both 3.3 kg m^{-3}).

As expected, the deficit N-fertilized and deficit irrigated treatment T5 yielded lowest. Yield of T6 was reduced due to N deficit compared to T2. When N-deficit fertilization took place, WPs were lowered (2.7 kg m^{-3} for T5 and 2.4 kg m^{-3} for T6). When WP and NUE were maximized (T5), WP was only 2.7 kg m^{-3} and NUE 41 kg grain kg N^{-1}. However, when fully irrigation took place and the optimization target was to maximize NUE (T6), the highest NUE of 58 kg grain kg N^{-1} was achieved. That means an increase of 22% compared to T2 and T3 and of 43% compared to T1, respectively.

Table 2. Total irrigation amount Virr, grain yield (at 15% humidity) in t ha^{-1}, total dry matter (TDM) in t ha^{-1}, water productivity (WP) in kg m^{-3}, total N-fertilization (N-fert) in kg N ha^{-1}, and nitrogen use efficiency (NUE) in kg grain kg N^{-1} for corn in 2010 (L´eau irriguée totale (Virr,) en mm, le rendement de grain (à humidité de 15%) en t ha^{-1}, la matière seche totale (TDM) en t ha^{-1}, la productivité d´eau (WP) en kg m^{-3}, l'application d'azote totale (N-fert) en kg ha^{-1} et l'efficacité de l'usage d'azote (NUE en kg kg^{-1} pour corn in 2010)

treatment	V_{irr}	grain yield	TDM	WP	N-fert	NUE
T1	231	7.7	13.2	3.3	234	33
T2	398	10.6	16.5	2.7	234	45
T3	289	10.5	16.3	3.6	234	45
T4	283	9.3	14.1	3.3	234	40
T5	225	6.0	10.3	2.7	147	41
T6	351	8.5	13.4	2.4	147	58

2.4 SPAD-Meter values

Flowering and begin of ripening of corn occurred around DAS 96 and DAS 128, respectively. As expected, the fully irrigated and fully N-fertilized treatment of T2 shows the highest chlorophyll contents. Due to some pests, yield of T1 was reduced. That is confirmed by the SPAD values of T1, the only ones decreasing sharply after about DAS 75. This decrease indicates the poor condition of the plants reflected by low chlorophyll contents (see Fig.2). Additionally, the N deficit condition of T5 and T6 are expressed by the high increases of SPAD values after each N-fertilization.

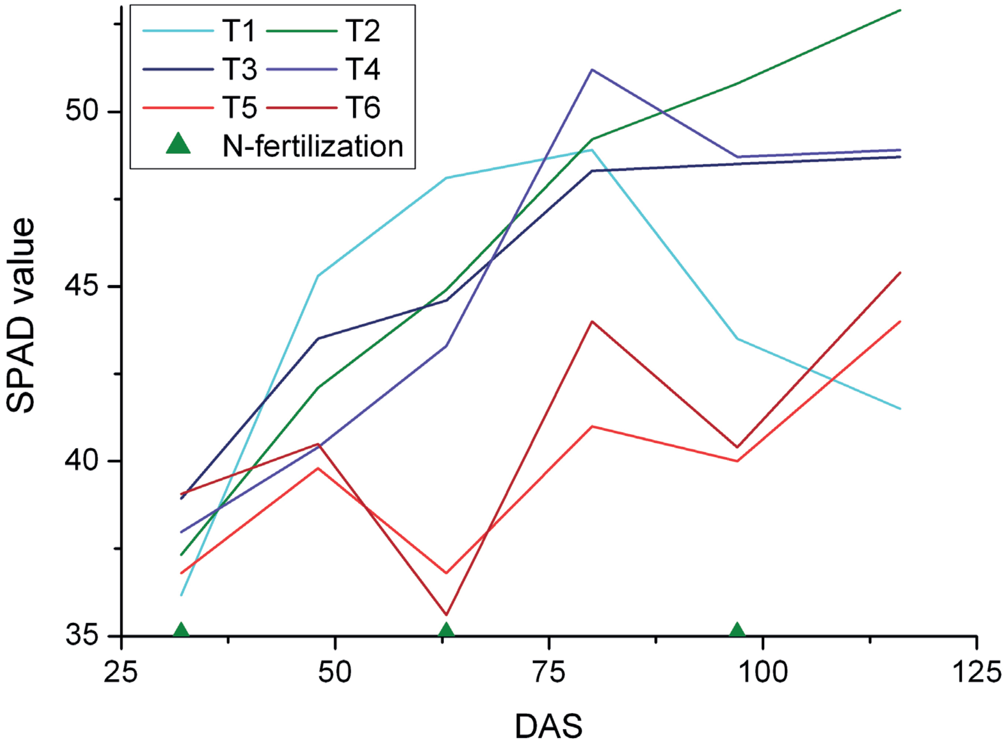

Figure 2. Chlorophyll Meter SPAD gives values which reflect the chlorophyll present in the plant leaves for all six treatments. N-fertilization events are marked green (Le chlorophylle-mètre nommé SPAD-Meter donne des valeurs qui reflètent la chlorophylle présente dans les feuilles pour les six traitements. Les applications de N sont marquées en vert)

3. DISCUSSION

The impact of drought stress and, in case of T5 and T6, N-stress was high, illustrated by grain yields varying from 6.0 to 10.6 t ha^{-1} for irrigation amounts of 231 to 398 mm and N-applications of 147 and 234 kg N ha^{-1}.

In general, reached WPs ranging from 2.4 to 3.6 kg m^{-3} are high compared to literature were WP ranged from 0.3 to 2.4 kg m^{-3} (Dehghanisanij et al., 2009; O'Neill et al., 2008; Rodrigues and Pereira, 2009). The optimization framework for irrigation scheduling was able to increase WP up to 25% within the full fertilized schedules, and 33% compared to the fully irrigated and deficit N-fertilized treatment T5. The high WPs of the tension controlled deficit irrigated treatments T3, T4 and T1 (60% of T2) indicate that an optimization of the soil tension threshold leads to high yields while saving water. However, the better performance of T3 compared to T4 was unexpected. Due to the adaption of the soil tension threshold to the crop growth period, e.g. to drought sensitive flowering in T4, a higher WP compared to T3 was expected. The reason may be an inadequate establishment of the growth stages or the soil tension thresholds.

In literature, NUE of corn ranges from about 26 to 55 kg grain kg N^{-1} (Barbieri et al. 2008; Di Paolo and Rinaldi, 2008; Varga et al., 2008), whereas NUE achieved in this study varied from 33 to 58 kg grain kg N^{-1}. Regarding the results of the deficit N scheduling at the fully irrigated treatment T6, the reached NUE is high (58 kg grain kg N^{-1}). However, NUE of 41 kg grain kg N^{-1} and WP of 2.7 kg m^{-3} of T5 were drought and N-stress occurred, are only moderate. It turns up that simulation based optimization of deficit irrigation or deficit N-fertilization were successfully carried out, but a combined optimization of both, irrigation and N-fertilization showed mean results.

4. SUMMARY AND CONCLUSIONS

There is a growing concern about excessive water and nitrogen use in agricultural systems due to reduced resource use efficiencies and increased groundwater pollution. Avoiding excessive water leakage through controlled irrigation and matching N application to crop N demand is the key to reduce N leaching and maintain crop yield. Such management requires knowledge of soil N dynamics as well as crop water and N demand. Simulation modeling can capture these interactions and is considered a powerful tool to assist optimization of irrigation and fertilization management.

In this research project, the simulation based optimization framework for irrigation and N-fertilization scheduling OCCASION was applied in order to compare different deficit irrigation and deficit N-fertilization strategies. The framework applied consists of the tailor-made evolutionary optimization algorithm GET-OPTIS and process-based SVAT-model DAISY for simulating water balance, nitrogen balance and crop growth. In 2010, an experiment was conducted where corn (*Zea mays L.*) was cultivated in container in a vegetation hall. We applied the optimization framework for optimizing irrigation and N-fertilization which were simultaneously and optimally distributed over one growing period to achieve maximum water productivity (WP) and nitrogen use efficiency (NUE). Three deficit irrigation schedules where determined via (i) irrigating of 60% of full irrigation, (ii) optimizing a constant soil tension threshold throughout the growth period, and (iii) optimizing a soil tension threshold that was adapted to the growth period of the crop. Additionally, a full irrigated control treatment with a soil tension threshold constant throughout the growth period was carried out. In two further treatments, irrigation and N-fertilization where optimized simultaneously which resulted in one treatment under N- and water limitation, and one N-limited but fully irrigated treatment. Moreover, the chlorophyll which is present in the plant leaves and closely related to the nutrimental condition of the plant was measured using a Chlorophyll Meter.

The results demonstrate that OCCASION can be successfully utilized to obtain high WPs. Within the optimized treatments, WP was increased up to 25% compared to the full irrigation treatment. NUE was highest for the fully irrigated deficit N-fertilized treatment (58 kg grain kg N^{-1}). It can be concluded that simulation based optimization of irrigation or N-fertilization is capable to enhance WP and NUE. However, at combined optimization of both, irrigation and N-fertilization performed only moderate.

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