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WATER USE EFFICIENCY OF SELECTED CROPS IN THE ROMANIAN PLAIN – MODEL STUDIES USING SENTINEL-2 SATELLITE IMAGES

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Abstract

The Romanian Plain is dominated by intensively used, fertile cropland with large agricultural potentials. Nutrient supply and water availability are major determinants of crop yields. Achievable yield is strongly influenced by fertilization and irrigation - depending on the local conditions. Increasing water use efficiency (WUE) is an important objective for distributing the limited water for irrigation. We present a study which determines scenario-based yields and WUE of winter wheat and maize throughout the Romanian Plain (2015–2017). The study compares results of the biophysical crop growth model PROMET with data on actual plant development derived from Sentinel-2 time series. Actual crop yields and WUE are compared to their potentials which are determined by assuming optimal fertilization for both rain-fed and optimal irrigated agriculture. The winter wheat simulations show that, under rain-fed conditions, optimal fertilization can more than double yields and maximize WUE, whereas irrigation hardly affects yield. Since maize is more affected by water stress in the Romanian Plain, optimal fertilization can double maize yields and maximize WUE under irrigation only.

Key words*: crop modeling, irrigation, Sentinel-2, water use efficiency, yield.*

INTRODUCTION

Implementing sustainable ways to secure food supply for a growing and wealthier global population is among the most important sustainable development goals (UN, 2015). In this objective, it is estimated that biomass production will have to roughly double by the year 2050 (Alexandratos and Bruinsma, 2012; Bruinsma, 2009). It has been shown that food production increase can be achieved globally through lifting the potentials of existing cropland rather than expanding into other land use categories (Mauser et al., 2015). The most important factors determining crop yield are climate, soils, water availability and agricultural management (esp. cultivar selection, timing of seeding, fertilization, irrigation, pest/weed control). In large agricultural regions, available rainfall limits yield either structurally (climate) or episodically (droughts). Good farm management adapts to the structural deficit by either limiting fertilizer inputs to the achievable rain-fed yields or by introducing irrigation to compensate the deficit and increase fertilizer inputs to the potential irrigated yields (or some solution in between). The second choice, introduction of deficit irrigation, can therefore considerably increase yields in many regions around the globe. On the farm scale, irrigation is a straightforward strategy as long as water is available. For water suppliers or administrative bodies, the question arises how much irrigation water is required to fulfill the cumulative irrigation water demands of a certain area. This question is complex, mainly because the conditions in terms of climate, soil and management are spatially heterogeneous and the profitability of irrigation may vary with farm size and crop type. Since deficit irrigation generally applies to regions with already scarce water resources, the main goal should be to allocate additional irrigation water to crop production in the most efficient way. Agricultural water use efficiency (WUE) is defined here as kg crop yield per m^3 evapotranspiration during the vegetation period. In general, agricultural WUE increases with yield, as unproductive evaporation from the soil and inter-

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ception from the leaves is minimized and productive transpiration is maximized to the extent possible when lifting yields (Zwart and Bastiaanssen, 2004). Irrigation WUE may also vary widely depending on irrigation technology, with flood irrigation being the least water efficient followed by sprinkler irrigation and drip irrigation being the most water efficient (Jägermeyr et al., 2015).

In this paper, we present first results of yield and related WUE simulations for winter wheat and maize in the Romanian Plain. The conducted simulations form an ensemble with scenarios of varying nutrient availability for the rain-fed case and an optimal nutrition scenario for both the rain-fed and irrigated case. Model simulations are carried out for the period 2015–2017. The potential role of increasing fertilization as well as additional irrigation on yields including corresponding WUE is analyzed for the comparatively dry years 2015 and 2017. In a first attempt, the simulated leaf area index (LAI) development of the ensemble simulations is compared to observed time series of the Sentinel-2 Earth Observation satellites for selected fields in the study region.

MATERIALS AND METHODS

The study region

The Romanian Plain, roughly the area between the Danube river and the Carpathian Mountains downstream the Iron Gate (Figure 1), is one of the most fertile agricultural regions in Europe.

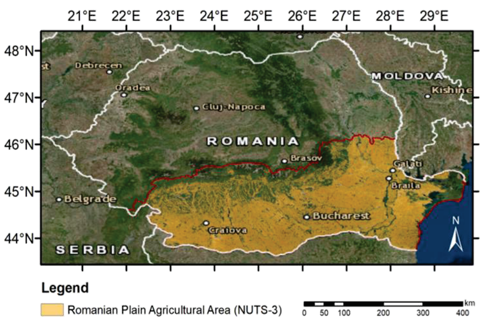

Figure 1. Agricultural area within the Romanian Plain (NUTS: Nomenclature of territorial units for statistics)

Efforts are currently underway to revitalize irrigation, which has been widespread during communist times and decayed in the first two decades after the end of the communist period in 1990. Furthermore, there are spatially diverse situations in the Romanian Plain, where fragmented agricultural lands alternate with large cropland areas belonging to major agricultural commercially oriented holdings (Balteanu and Popovici, 2010). Thus, a great variety of land use management practices is present implying diverse situations of resource allocation and use, especially in terms of water and fertilization.

Climate in the Romanian Plain is warm-semiarid with average temperatures ranging from above 9°C in the North to above 11°C in the South and annual rainfalls from 600–700 mm in the North to 500–600 mm in the South. Aridity increases from North to South with Thornthwaite aridity index values in the range of 40–55% (Dragota et al., 2011).

The conceptual approach of yield scenarios and agricultural WUE determination

WUE connects yield with either productive plant water consumption (transpiration) or both productive and unproductive water losses (evapotranspiration). It is straightforward to consider total evapotranspiration within the crop vegetation period for WUE assessment as true water losses from the agricultural system should be considered. Concerning yield, we closely relate to the definitions of yield scenarios given by van Ittersum and Rabbinge (1997) (Figure 2), who differentiate between potential, water-limited, water and nutrient-limited and actual yield. In the Romanian Plain, we assume that actual yield is mainly limited by both water and nutrient availability.

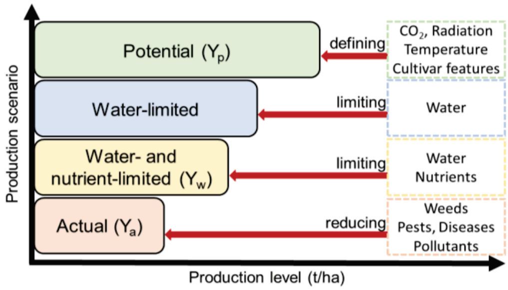

Figure 2. Yield definitions and limitations for the Y_a, Y_w and Y_p scenarios used in this paper (adapted from: van Ittersum and Rabbinge, 1997)

We therefore investigate yield and WUE for three cases: i) potential (Y_p: abundant water and nutrient supply), ii) water-limited (Y_W: only water supply limiting) and iii) actual yield (Y_a: water and nutrient supply limiting).
There is no direct way to map WUE since its determining parameters, evapotranspiration and yields are hardly accessible in a spatial way. Their interrelation though can be modeled with mechanistic crop growth models giving insight into the coupled processes of yield formation and water flows. Simulating potential and water-limited yield as well as corresponding WUE is straightforward by assuming that either nutrients and water or only nutrients are abundant. Models though need additional information to simulate actual yields and related WUE. In this objective, a combination of crop growth ensemble simulations using the model PROMET (Mauser and Bach, 2009) and information from Sentinel-2 satellite data is used. Sentinel-2 offers new observational capabilities to determine time series of crop leaf development with high temporal and spatial resolution. The PROMET ensemble member's represent variety of farm management options regarding fertilization. Actual yields, WUE and water scarcity are determined from a comparison of measured and simulated crop leaf development. This approach (schematically shown in Figure 3) was already successfully applied by Hank et al. (2015) and allows obtaining information of large coverage and high-resolution in a timely manner.

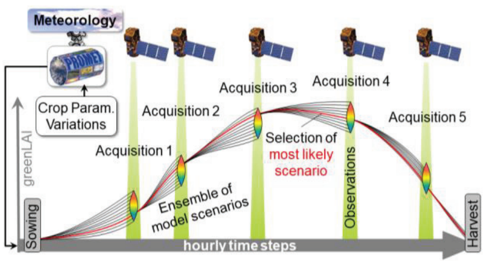

Figure 3. The approach to combine an ensemble of PROMET crop growth simulations with Sentinel-2 observations to determine actual yields and WUE (Hank et al., 2015)

The COPERNICUS Sentinel-2 satellites

The data stream created by the European COPERNICUS satellite observation system (ESA, 2018) opens up new possibilities for the observation of growth of individual crops down to the plot scale by monitoring the development of LAI. Sentinel-2 observes the land surface with 9 spectral bands at a spatial resolution of 10/20 m and a revisit time of 5 days at the equator. LAI can accurately be derived from the Sentinel-2 images by applying atmospheric corrections and subsequent inversion algorithms for the radiative transfer in the canopy of the crops, which includes all available spectral bands of Sentinel-2 (Migdall et al., 2009; Verhoef and Bach, 2012). The LAI time series are available at a spatial resolution of 10 m and, depending on cloud cover, a temporal resolution of ~10 days.

The Crop Growth Model PROMET

The dynamic biophysically based and spatially explicit agro-hydrological model PROMET (Mauser and Bach, 2009; Hank et al., 2015) simulates actual and potential agro-ecological yields and water flows. It is used to model the development of winter wheat and maize, which represent more than 50% of the acreage in the Romanian Plain (INS, 2018). PROMET simulates net primary production with a dynamic first order plant-physiology approach (Farquhar et al., 1980) and uses a canopy model to allocate assimilate to plant organs. In this study, geographical data on topography (Farr et al., 2007), soil (FAO, 2012) and acreage (EEA, 2012) is used at a spatial resolution of 30”; actual sowing dates and information on the long-term course of phenology were derived from JRC AGRI4CAST (2015).
As meteorological input driver, the ERA-Interim reanalysis product of ECMWF (Dee et al., 2011) was used. Within PROMET, ERA-Interim data was downscaled from 0.5° to 30” spatial resolution and disaggregated from six-hourly to hourly temporal resolution. Meteorological driver data was simultaneously bias-corrected using spatially distributed monthly correction factors derived from the WorldClim climatology (Hijmans et al., 2005).
Crop growth and water balance was simulated on an hourly basis and at a spatial resolution of 30” for winter wheat and maize being in each case cultivated on the whole acreage of the Romanian Plain. Simulations were carried out-

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from 1 September 2014 to 31 October 2017, thereby covering most of the period in which Sentinel-2 data is available. Crop specific water, nutrient and temperature stress as well as actual CO_2 concentrations are physiologically considered. These factors influence agro-ecological yields through phonological development, CO_2 fertilization and yield formation and finally lead to a successful or failed harvest.

Yield ensemble simulations for winter wheat and maize comprise scenarios of a systematical variation of the PROMET nutrition factor (NF) in the rain-fed case. The NF represents nutrient availability (nitrogen and phosphorus) to the crops and was logarithmically increased from 0.2 (very low nutrient level) to 0.55 (no nutrient deficit). In addition, an optimal nutrition scenario is simulated for both the rain-fed and the irrigated case. In this model study, irrigation is conceptualized through a total elimination of plant water stress by holding soil water content permanently at field capacity. For all scenarios, LAI, evapotranspiration and crop water stress were aggregated to daily values and were analyzed together with annual yields.

RESULTS AND DISCUSSIONS

The LAI ensemble

The nutrient ensemble results of the LAI development courses for an exemplary location in the eastern part of the Olt sub-unit within the Romanian Plain are depicted in Figure 4 for winter wheat (top) and maize (bottom). LAI development varies strongly with nutrient availability. For winter wheat, nutrient supply does not alter the length of the growing season, which is rather weather dependent. In contrary, maize simulation results show that the length of the growing season is influenced by both weather conditions and nutrient availability as higher nutrition status may trigger crop water stress. Yearly variability's can be noticed in both cases.

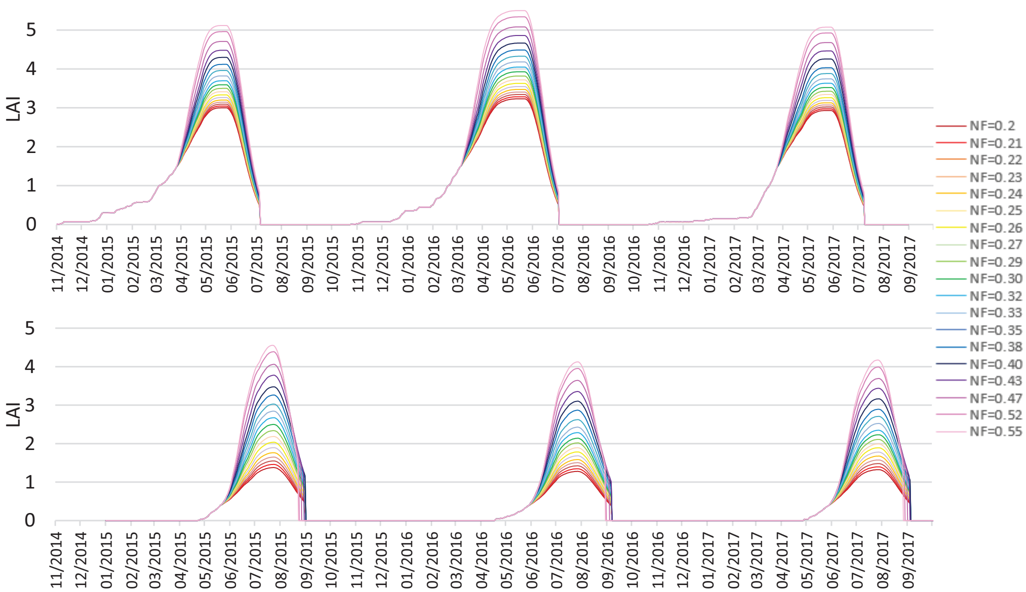

Figure 4. Simulated LAI development from 1 November 2014 to 30 September 2017 for winter wheat (top) and maize (bottom) at an exemplary location in the Romanian Plain for an ensemble of nutrient availability (NF) ranging from 0.2 (very low nutrient supply) to 0.55 (no nutrient limit)

Winter wheat and maize sensitivity to water stress

The reason for the difference in behavior of the two crops becomes evident in Figure 5. Here, sensitivity functions of simulated yield, crop water stress and WUE to nutrient availability are shown in a spatial average of the Romanian Plain for winter wheat (Figure 5, top) and maize (Figure 5, bottom) for an ensemble of the water-limited nutrient supply scenarios. The drought year 2015 was chosen for this assessment to shed light on the crop's reaction on comparatively severe water stress within the period of study. Crop water stress is detected by the model as soon as the plant experiences transpiration deficits due to soil water shortages and is expressed by a normalized index ranging from 1 (no water stress) to 0 (max. water stress: no transpiration possible) over the whole vegetation period. A water stress index value of 0.8 is in the magnitude of severe water stress with considerable yield losses as a consequence.

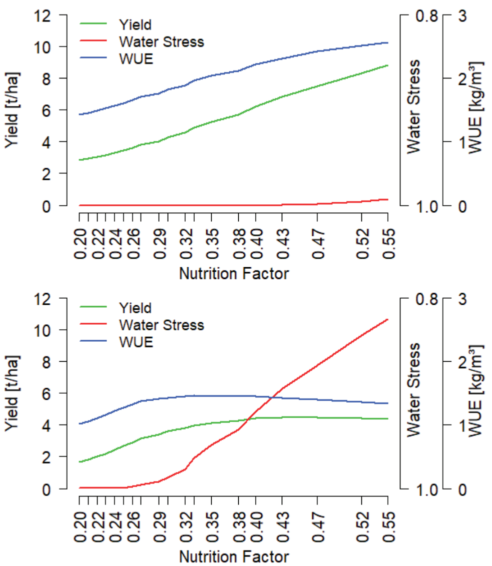

Figure 5. Sensitivity functions of simulated yield, crop water stress and WUE to nutrient availability of winter wheat (top) and maize (bottom) for the drought year 2015 in spatial average for an ensemble of nutrient availability scenarios ranging from NF=0.2 (very low nutrient supply) to NF=0.55 (no nutrient limit)

Increasing fertilization of winter wheat leads to a yield increase from 2.83 t/ha to 8.83 t/ha in spatial average. Fertilization and increasing yields coincide with a WUE, which increases from 1.42 kg/m³ to 2.57 kg/m³. Due to its early development, winter wheat does not show any water stress signal for NF < 0.43. Simulations therefore suggest that winter wheat yield is solely limited by the nutrition supply in the Romanian Plain even during the drought year 2015. The situation for maize is completely different. Yield level rises with increasing fertilization from 1.68 t/ha to a saturation level of 4.49 t/ha at NF = 0.47. Similarly, WUE increases from 1.01 kg/m³ to a saturation level of 1.46 kg/m³ at NF = 0.33. Water stress already sets in at NF = 0.25 and reaches a maximum stress level of 0.82, making additional fertilizer application increasingly useless until the impact of water stress finally overrides benefits from increasing fertilization. At higher fertilization levels, maize yields and WUE decrease down to 4.37 t/ha and 1.33 kg/m³. This is due to an earlier development of the crop caused by water stress, which consumes available water for leaf development and leads to diminished fruit formation. Water stress accelerates phenology call development and also leads to earlier harvests as a result of premature ripening (Figure 4, bottom). Therefore, simulations show that maize yield is limited by both nutrition and water supply in the Romanian Plain during the drought year 2015.

Yield scenarios for winter wheat and maize in 2017

From the findings of Figures 4 and 5, appropriate NF values were selected representing the actual, water-limited and potential yield scenarios (Table 1).

Table 1. Selected NF values for the yield scenario simulations for 2015–2017 in the Romanian Plain

Scenario	NF Winter Wheat	NF Maize
Y_a	0.27	0.33
Y_w	0.55 (rain-fed)	0.55 (rain-fed)
Y_p	0.55(irrigated)	0.55(irrigated)

NF values for actual yield levels represent fertilizer application levels assumed to be approx. 45 kg/ha for winter wheat and 55 kg/ha for maize (GFA Terra Systems, 2004; NISCAD, 2018). NF values for water-limited yields (rain-fed) and potential yields (irrigated) represent

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high intensity farming with fertilizer application levels of approx. 250 kg/ha.
Figure 6 shows the spatial distribution of the actual (top), water-limited (center) and potential yields (bottom) for winter wheat (left) and maize (right) in the whole Romanian Plain exemplary for the year 2017.
The simulated actual winter wheat yield amounts to a low value of 3.74 t/ha in average; its patterns form a very slight, but general gradient from East to West, which is caused mainly by decreasing radiation. The Northern Piedmont regions of the Plain generally show slightly lower yields due to reduced air temperatures and thus lower temperature sums. Winter wheat yields sharply increase with increasing fertilizer application to 8.97 t/ha in average (Figure 6, left, center), but there is hardly any difference between water-limited (Figure 6, left, center) and potential (Figure 6, left, bottom; 8.98 t/ha in average) yield as winter wheat did not experience any water stress in the Romanian Plain in 2017.

Likewise, the situation for maize differs largely from the winter wheat findings. The simulated actual maize yield amounts to 4.23 t/ha in average. It shows a more pronounced but similar pattern as winter wheat with a gradient in yield from NE to SW. Both water stress and waste of fertilizer is avoided by keeping the nutrition status on a relatively low level. Reducing nutrient stress by optimal fertilizer application in the rain-fed case, water-limited maize yield (Figure 6, right, center) shows only a mild increase to an average of 5.59 t/ha and a strong differentiation in yield according to the underlying soil conditions in the model inputs. Soils with high water holding capacities like in the alluvial plain in the East tend to allow higher yields than sandier soils in the West, where fast percolation enforces water stress. Removing water stress through additional irrigation (Figure 6, right, bottom) leads to a simulated potential maize yield to an average level of 10.18 t/ha and a spatial homogenization of yield levels.

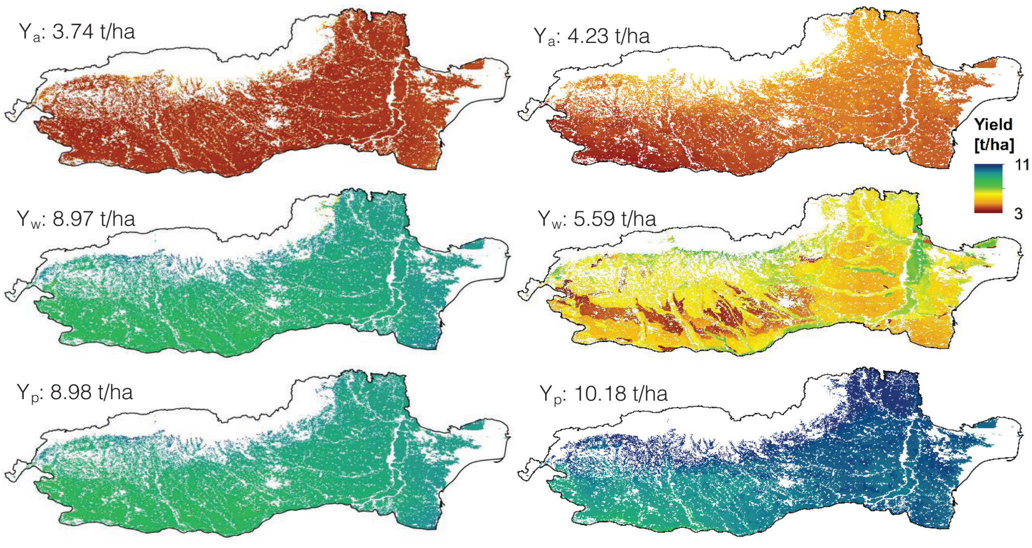

Figure 6. Spatial distribution of simulated actual (top), water-limited (center) and potential (bottom) yield of winter wheat (left) and maize (right) in 2017 in the Romanian Plain

This demonstrates the very high potential for increasing winter wheat and maize yields in the Romanian Plain. Simulations show that in the case of winter wheat, increasing fertilization and in the case of maize, increasing fertilization and additional irrigation is the key to lift yield levels.

WUE scenarios for winter wheat and maize in 2017

Hereafter, WUE assessments are shown in correspondence to the achieved scenario yields. Figure 7 depicts the spatial distribution of the related WUEs for the actual (top), water-limited (center) and potential scenarios (bottom) for winter wheat (left) and maize (right) in the Romanian Plain exemplary for the year 2017.

Actual winter wheat WUE reaches 1.70 kg/m³ on average. Through optimal fertilization in the rain-fed case, a sharp increase of average WUE to 2.62 kg/m³ can be achieved. By irrigation as a surplus to optimal fertilization, average WUE (2.12 kg/m³) slightly declines as there is no significant yield increase in the potential scenario, but higher water losses as most of the additional irrigation water is unproductively evaporated, leading to a lowering of WUE.

In contrast, actual maize WUE amounts to 1.57 kg/m³ on average. With optimal fertilization, average WUE (1.56 kg/m³) even decreases due to water stress and yield losses. Regions which already show water stress in the actual scenario are particularly affected. By irrigation as a surplus to optimal fertilization, average WUE (1.80 kg/m³) increases over the actual WUE level as crop water consumption is not restricted during dry season anymore and can properly contribute to yield formation.

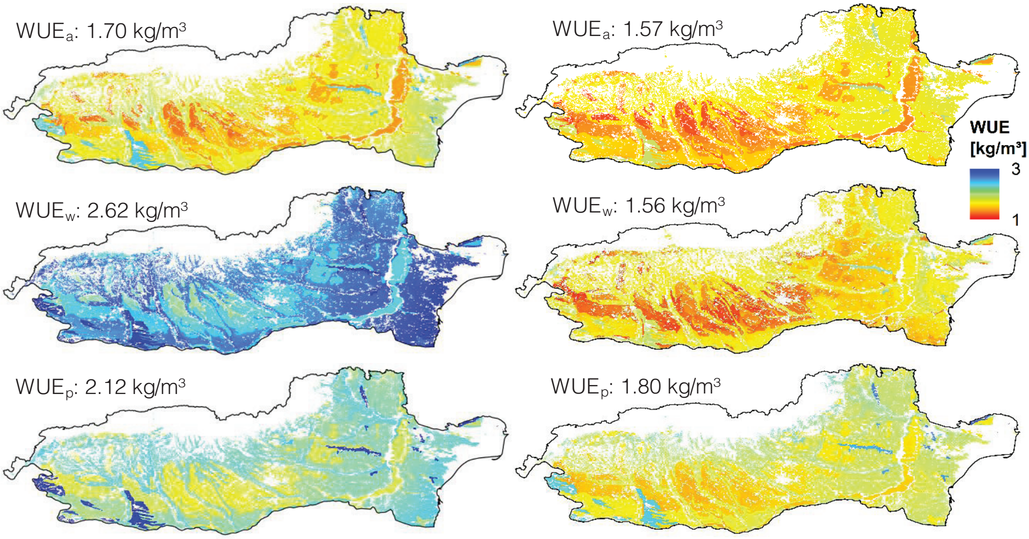

Figure 7. Spatial distribution of simulated actual (top), water-limited (center) and potential (bottom) WUE of winter wheat (left) and maize (right) in 2017 in the Romanian Plain

Again, the spatial patterns depicted in all WUE maps clearly hint at the strong relationship of WUE with the water holding capacities of the soils.

The scatterplots (Figure 8) give insights into the scenario specific yield-WUE-relationships. Here, the dependence of simulated actual (left), water-limited (center) and potential (right) WUE of winter wheat (top) and maize (bottom) on their respective yields in the period 2015-2017 in the Romanian Plain are shown. The highest yielding scenarios largely coincide with the scenarios of highest WUE. Simulations show that in the case of winter wheat, yield can be maximized under highest WUE by increasing fertilization. In the case of maize, highest yields under highest WUE can be achieved by increasing fertilization and additional irrigation.

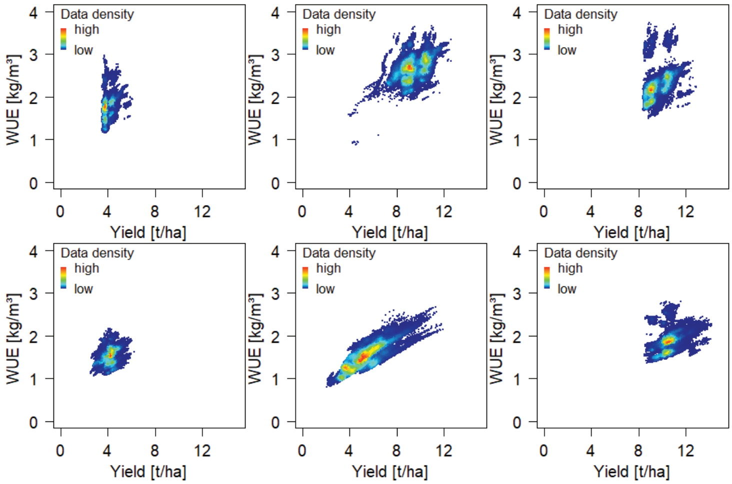

Figure 8. Scatterplots of the relationship of simulated actual (left), water-limited (center) and potential (right) WUE of winter wheat (top) and maize (bottom) and their respective yields in 2015–2017 in the Romanian Plain. Each data point represents the yield-WUE-relationship of one pixel in the study region in one year out of the period 2015–2017

Comparison of simulated and inverted sentinel-2 LAI

Sentinel-2 data is available from July 2015 onwards. Since the launch of Sentinel-2B, two identical satellites are orbiting the Earth, reducing the theoretical revisit time to between 2and 5 days in the Romanian Plain.

The sub-section ROU005 (Figure 9) of tile 34TGQ was chosen for the comparison of modeled and inverted LAI. A total of 75 completely or partly cloud-free images of 2015–2017 were processed using an inverse modeling approach to determine land-use and LAI from all Sentinel-2 spectral bands for each 10 m x 10 m pixel (Bach et al., 2016; Migdall et al., 2009).

The exemplary Sentinel-2 satellite image (sub-section ROU005 on 21 April 2016) in Figure 9 shows a false color composite of the spectral bands red (R), NIR (G) and MIR (B).

It includes rural villages (e.g. on the left and right side of the image) and covers all field sizes from extremely small fields in the vicinity of the villages to large and intensively used fields in the North and South.

An inoperative irrigation canal can be identified running through the upper part of the image from the left side to the upper right corner. The different shades of green indicate different development stages of spring-active winter cereals.

Figure 9. Sub-section ROU005 of Sentinel-2 tile 34TGQ observed on 21 April 2016

In some fields, specifically in the lower part of the image, different growth conditions related to soil and geomorphological differences can be recognized within the fields. Other fields showing no greenness do not carry vegetation at this stage of development and will most likely develop summer-active crops like maize, sunflower or sugar beet.

From the selected and processed Sentinel-2 images, the temporal development of LAI was extracted and analyzed. Figure 10 shows the LAI development during the season of 2016 for three selected neighboring winter wheat fields together with the nutrient ensemble of simulated winter wheat LAI developments at the respective location.

Figure 10 shows commonalities as well as differences between the simulated and observed LAI developments. In general, the date of peak LAI roughly coincides between simulation and observations. The simulated LAI development as well as the observed LAI development at EO2 already starts in early spring whereas the observed LAI at EO1 and EO3 starts to increase as late as mid to end of March. Harvest date in the simulated winter wheat development occurs at the beginning of July, which is in accordance with EO observations. Winter wheat vegetation period as simulated by PROMET coincides with the observed vegetation period at the EO2 field.

The EO1 field shows no sign of green leaves during winter, which is most likely due to frost damage during the cold season. This may also explain the retarded and poor development and consequently low LAI peak values on that field.

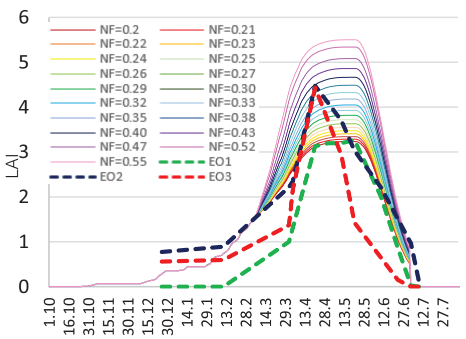

Figure 10. Comparison of the simulated nutrition ensemble of LAI development (solid lines) and the LAI development of three selected winter wheat fields in the Romanian Plain derived from a time series of Sentinel-2 images for the season of 2015/2016 (dashed lines)

However, absolute peak LAI values of the selected fields satisfactorily cover the range of LAI simulated for 2016 by varying the nutrition factor in PROMET. Comparing peak LAI of the three fields may suggest a low yield of approx. 3 t/ha at EO1, whereas the yields at EO2 and EO3 could be of the order of 7 t/ha.

These findingshintat pronounced spatial heterogeneities on an even small scale between neighboring fields, which pose great challenges to crop model studies in the Romanian Plain. Further studies should focus on a refinement of crop parameterization accounting for the special sub-regional and local realities in the Plain, markedly the favoring climatic conditions and very fertile soils in combination with most variable nutrient management and water shortages during mid-summer. Thus, a major perception of the study is that Sentinel-2 satellite time series are an important source of information to understand the agricultural realities in the Romanian Plain.

CONCLUSIONS

Simulations were carried out with the crop growth model PROMET to investigate the relation between yield and WUE for three different scenarios: i) actual yield, ii) water-limited yield and iii) potential yield of winter wheat and maize in the Romanian Plain. The simulation period covered the years 2015 (dry), 2016 (wet) and 2017 (normal to slightly dry).

Winter wheat and maize show a distinctly different behavior in the study region in 2015–2017. Winter wheat is hardly affected by water stress; its yield is therefore mainly determined by the fertilization level, which is generally low in the Romanian Plain. Even with optimal fertilizer application, water stress is not a limiting factor for winter wheat. Maize does not show severe water stress under the actual level of fertilization. By raising fertilization in contrast, water stress intensity increases drastically and can in some regions even lead to yield reductions compared to yields levels achieved by current management practice. This suggests that farmers who do not introduce irrigation do not waste fertilizer unproductively likewise.

An assessment of the efficiency of water used to achieve a certain amount of yield is vital in regions prone to water stress such as the Romanian Plain. The WUE of winter wheat tends to increase to high levels with increasing yields and fertilizer application. This does not hold for maize where WUE stagnates at medium levels and even decreases with high nutrition factors. Only by introducing irrigation on top of fertilization, maize WUE can be increased significantly. Our simulations show that irrigation does not affect winter wheat yield much, whereas it can more than double current maize yield.

The preliminary results of the comparison of simulated and Sentinel-2 derived LAI development are promising. They show that the satellite observations point at improvements in the region dependent parameterization of the crop models. Further steps in the analysis of the Sentinel-2 time series will further clarify and stabilize the results and will lead into the direction of field specific model parameter derivation from satellite time series.

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REFERENCES

Alexandratos N., Bruinsma J., 2012. World Agriculture Towards 2030/2050: the 2012 Revision. ESA Working Paper No. 12-03. FAO, Rome.

Bach H., Migdall S., Brohmeyer F., Brüggemann L., Buddeberg M., 2016.Satellitengestützte Ertragserhebung. Schriftenreihe des LfULG, Heft 21/2016. Landesamt für Umwelt, Landwirtschaft und Geologie Sachsen. https://publikationen.sachsen.de/bdb/artikel/13631 (last visited: 14.06.2018).

Balteanu D., Popovici E.A., 2010. Land use changes and land degradation in post-socialist Romania. Rom. Journ. Geogr., 54(2): 95–105.

Bruinsma J., 2009: The Resource Outlook to 2050: By How Much Do Land, Water Use and Crop Yields Need to Increase by 2050. Technical Papers from the Expert Meeting on 'How to Feed the World in 2050'. 1–33. FAO, Rome.

Dee D.P., Uppala S.M., Simmons A.J., Berrisford P., Poli P., Kobayashi S., Andrae U., Balmaseda M.A., Balsamo G., Bauer P., Bechtold P., Beljaars A.C.M., van de Berg L., Bidlot J., Bormann N., Delsol C., Dragani R., Fuentes M., Geer A.J., Haimberger L., Healy S.B., Hersbach H., Hólm E.V., Isaksen L., Kållberg P., Köhler M., Matricardi M., McNally A.P., Monge-Sanz B.M, Morcrette J.-J., Park B.-K., Peubey C., deRosnay P., Tavolato C., Thépaut J.-N., Vitart F., 2011. The ERA-Interim reanalysis. Configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc., 137: 553–597.

Dragota C.-S., Dumitrascu M., Grigorescu I., Kucsicsa G., 2011. The Climatic Water Deficit in SouthOltenia Using the Thornthwaite Method.Forum geografic. Studii si cercetari de geografie si protectia mediului,10(1): 140–148.

EEA– European Environment Agency, 2012.Copernicus Land Service – Pan-European Component: CORINE Land Cover (CLC2012).

ESA– European Space Agency, 2018. https://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Overview3 (last visited: 03.06.2018).

FAO – Food and Agriculture Organization of the United Nations, 2012. Harmonized World Soil Database (version 1.2). FAO, Rome and IIASA, Laxenburg.

Farquhar G.D., von Caemmerer S., Berry J.A., 1980.A biochemical model of photosynthetic CO_2 assimilation in leaves of C_3 species. Planta, 149(1): 78–90.

Farr T.G., Rosen P.A., Caro E., Crippen R., Duren R., Hensley S., Kobrick M., Paller M., Rodriguez E., Roth L., Seal D., Shaffer S. Shimada J., Umland J., Werner M., Oskin M., Burbank D., Alsdorf D., 2007. The Shuttle Radar Topography Mission. Rev. Geophys. 45, RG2004.

GFA Terra Systems, 2004. Inventory of Mineral Fertiliser Use in the Danube River Basin Countries with Reference to Manure and Land Management Practices. Danube Regional Project – Project RER/01/G32. Final Report. https://www.icpdr.org/main/sites/default/files/1.2-3_Fertiliser%20Inventory%20-%20FINAL.pdf (last visited: 14.06.2018).

Hank T.B., Bach H., Mauser W., 2015.Using a Remote Sensing-Supported Hydro-Agroecological Model for Field-Scale Simulation of Heterogeneous Crop Growth and Yield: Application for Wheat in Central Europe, Remote Sensing, 7(4):3934–3965.

Hijmans R.J., Cameron S.E., Parra J.L., Jones P.G., Jarvis A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol., 25(15): 1965–1978.

INS – National Institute of Statistics Romania, 2018. Productia vegetala la principalele culturi, in anul 2017. http://www.insse.ro/cms/ro/content/produc%C5%A3ia-vegetal%C4%83-la-principalele-culturi-%C3%AEn-anul-2017 (last visited: 19.06.2018).

van Ittersum M.K., Rabbinge R., 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Research, 52(3): 197–208.

Jägermeyr J., Gerten D., Heinke J., Schaphoff S., Kummu M., Lucht W., 2015. Water savings potentials of irrigation systems: global simulation of processes and linkages. Hydrol. Earth Syst. Sci., 19: 3073–3091.

JRC AGRI4CAST – Joint Research Center, 2015. Crop Calendar (MARS), http://agri4cast.jrc.ec.europa.eu/DataPortal/ (last visited: 14.06.2018).

Mauser W., Bach H., 2009. PROMET – Large scale distributed hydrological modelling to study the impact of climate change on the water flows of mountain watersheds. Journal of Hydrology, 376(3/4): 362–377.

Mauser W., Klepper G., Zabel F., Delzeit R., Hank T., Putzenlechner B., Calzadilla A., 2015. Global biomass production potentials exceed expected future demand without the need for cropland expansion. Nat. Commun., 6:8946.

Migdall S., Bach H., Bobert J., Wehrhan M., Mauser W., 2009. Inversion of a canopy reflectance model using hyperspectral imagery for monitoring wheat growth and estimating yield. Precision Agriculture, 10(6): 508–524.

NISCAD– National Institute of Statistics and County Agricultural Directions of Romania, 2018. Pers. Comm.

UN – United Nations, 2015.Indicators and a Monitoring Framework for the Sustainable Development Goals. Launching a Data Revolution. A report to the Secretary-General of the United Nations by the Leadership Council of the Sustainable Development Solutions Network.http://unsdsn.org/indicators (last visited: 14.06.2016).

Verhoef W., Bach H., 2012. Simulation of Sentinel-3 images by four stream surface atmosphere radiative transfer modeling in the optical and thermal domains. Remote sensing of environment, 120: 197–207.

Zwart S.J., Bastiaanssen W.G.M., 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agricultural Water Management, 69(2): 115–133.

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Virtual Water Values