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Modelling irrigation demand from two grasslands in Switzerland under contrasting climatic conditions and soil properties

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Abstract: We examine irrigation demand in Switzerland under current climatic conditions on the basis of simulations with a process-based grassland model. Two sites are considered: Oensingen, on the Swiss Plateau, benefits from a humid climate and is rarely affected by drought; Sion, located in the Rhone Valley, is highly water-limited, with critical soil moisture conditions every year. Water requirements to sustain productivity therefore vary substantially between the sites and in time, with needs up to 800 mm per year at Sion, and average needs of the order of 300 mm at Oensingen if a shallow soil is assumed. We show that simple relations can be found between water requirements and key variables such as the so-called atmospheric water budget, i.e. the difference between precipitation and potential evapotranspiration. Such relations are not only useful to quantify water requirements at other sites, but also for assessing the benefits of irrigation. At Sion, we find for instance that even while restricting the water requirement fulfilment to 500 mm per year, irrigation can increase productivity by 9 t/ha compared to a rainfed situation.

Keywords: Grassland model; Water deficiency; Yield; Irrigation requirement; Switzerland

1. INTRODUCTION

Drought can significantly affect agricultural production. In Europe this is currently the case mainly in the Mediterranean area and in the South-East [IPCC, 2007]. However, climate scenarios developed under PRUDENCE [Christensen et al., 2007] suggest that the situation could change in the future. In fact, a decrease in summer rainfall and associated increase in summer heat-waves is projected in many areas, including Switzerland and the Alps [Calanca, 2007]. In this respect, the summer heat wave of 2003, with its negative impacts on terrestrial ecosystems, is considered by many as a shape of things to come [Schär, 2004; Ciais et al., 2005; Smith et al., 2010].

Coping with more frequent dry and hot episodes during the growing season is a challenge for farmers. Increasing the share of irrigated land could be one of the possibilities to face more frequent droughts. In Switzerland for instance, several regional governments are currently examining options in this direction [Lehman et al., 2001; Fuhrer & Jasper, 2009; <http://www.acqwa.ch>]. However this could lead to water use conflicts with other economical sectors, as well as to water waste, higher production costs, erosion and nutrient leaching. Moreover, irrigation could affect the local climate in different ways: moist and dark soils absorb more energy from the sun due to a reduced reflectivity which tends to warm the surface, but available moisture allows the soil-vegetation system to respond to the atmospheric demand by evaporating and transpiring more [Boucher et al., 2004].

Simulation models enable to better understand water demand and consumption in agriculture. They can be used for sensitivity analysis and to explore the implication of projections from climate scenarios. In this study we applied the PROductive GRASSland Simulator (PROGRASS [Lazzarotto et al., 2009]) to investigate the water balance of

grassland ecosystems in two contrasted areas of Switzerland: The Swiss Plateau and the Rhone Valley. On the Swiss Plateau summer precipitation (total amount during June, July and August) is equivalent to about 400 mm in the long-term, implying drought conditions only every tenth year on average [Calanca, 2004]. In contrast, the Rhone Valley, with only 150 mm of precipitation during summer, is characterized by a dry climate. Water deficit during the growing season is therefore a recurrent phenomenon.

In Lazzarotto et al. [2009, 2010], PROGRASS was applied to study the effect of climate change on grassland dynamics and nutrient cycling. The water balance was not addressed directly. To be able to investigate water demand and consumption under varying climatic conditions and soil properties, improvements to PROGRASS in a number of features were needed. Presenting these improvements and the investigation results for both contrasting sites is the aim of this paper.

2. STUDY SITE CHARACTERISTICS

Location and physiographic characteristics of the two sites considered for the present investigation are given in Figure 1 and Table 1.

Oensingen (Oe) is located on the Swiss Plateau and is characterized by a humid climate, with an annual precipitation of 1150 mm and a mean annual temperature of 9.2 °C. The heavy soil (stagnic cambisol eutric, 43 % of clay) has an estimated maximum water storage capacity of 416 mm for a rooting depth of 800 mm. At this site, several aspects of grassland dynamics related to carbon, nitrogen and water cycling have been investigated experimentally since 2001 [Ammann et al., 2007, 2009].

Sion (Si), located in the Rhone Valley (South-western Switzerland), is characterized by a dry climate, with an annual precipitation of 610 mm and an annual mean temperature of 10.3 °C. The soil is a sandy loam, with an estimated maximum water storage capacity of 53mm, for a rooting depth of 130 mm. Both values were estimated based on information available from the Swiss soil suitability map [BFS, 2004].

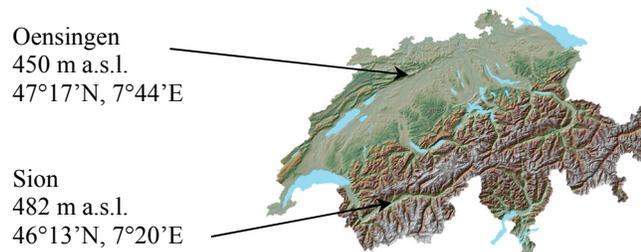


Figure 1 - Study site locations in Switzerland's topography

Table 1 – Soil properties at Oensingen and Sion. θ_{sat} , θ_{fc} and θ_{pwp} are the volumetric soil moisture content [mm water/mm soil] at saturation (porosity), field capacity and the permanent wilting point, respectively. θ_{crit} is the soil moisture threshold considered for computing water requirements. It is assumed that below this threshold drought stress starts limiting plant growth.

	Rooting depth [mm]	% sand	% silt	% clay	θ_{sat}	θ_{fc}	θ_{crit}	θ_{pwp}
Oensingen	800	25	32	43	0.52	0.46	0.35	0.22
Sion	130	65	25	10	0.41	0.36	0.12	0.09

3. METHODS

3.1 PROGRASS and its extensions

Originally, PROGRASS was designed to simulate grassland growth in mixed grass/clover swards in response to climate and management. It uses a bucket approach to estimate the soil water balance, where inputs are from precipitation minus interception and outputs are from evapotranspiration and drainage [Lazzarotto et al., 2009]. The model does not consider lateral water movement or water ponding at the surface. Water in excess of the infiltration capacity is removed as surface runoff.

Our extensions include a better formulation of rainfall interception that entails inhibition of transpiration while the intercepted water store evaporates, and an explicit formulation of capillary rise (Q_{cap}) from external groundwater. The latter prevents soil moisture from crossing the permanent wilting point in very dry conditions. To compute the soil moisture budget, at each hourly time step, losses from evapotranspiration (ET) and drainage (Q_{drain}) are first subtracted from the available soil water store. Subsequently, non-intercepted precipitation (P) is allowed to infiltrate as long as pore space is available, otherwise surface runoff is generated (Q_{surf}).

Concerning ET, the model distinguishes between potential ET (pET), which represents the water uptake under optimum growing conditions, and actual evaporation and transpiration (aET), which depends on soil moisture status. For all processes, drought stress is defined with respect to specific soil moisture thresholds [Lazzarotto et al. 2009], which in most cases are close to θ_{crit} as given in Table 1.

To test the new formulation of the water balance, water fluxes simulated at Oensingen were compared to experimental data. We found that daily, seasonal and interannual variations of aET correlate well with observations, in spite of a slight tendency of the model to overestimate day-to-day variability and to underestimate the annual mean. Soil drying and wetting phases in response to precipitation events and losses by drainage, runoff and ET, including the duration and severity of the 2003 drought, were well captured by the model (data not shown).

3.2 Computation of water requirements

In Fuhrer & Jasper [2009], needs for irrigation were examined relatively to critical thresholds in the ET efficiency, defined as the ratio aET / pET . In the present study, we directly computed the amount of water required to fulfil the climatic demand (pET) and sustain potential growth in simulations for non-water-limited (Nwl) conditions. In order to estimate ET efficiency and productivity gains we compared these simulations with that for rainfed (Rf) conditions. This results in four output datasets (Oe_{Rf} , Oe_{Nwl} , Si_{Rf} , Si_{Nwl}). In practice, water requirement ($Wreq$) is defined as the amount of water needed to maintain soil moisture just above the critical level θ_{crit} . Note that $pET_{Rf} \neq pET_{Nwl}$ because keeping soil moisture above the critical level increases the Leaf Area Index (LAI). Moreover, $aET_{Nwl} = pET_{Nwl}$. In the following, if not stated otherwise, pET refers to pET_{Nwl} and aET to aET_{Rf} .

3.3 Simulation setup and initialization

All simulations were run for 28 years using hourly weather data for 1981-2008 as recorded by the Swiss Federal Office for Meteorology and Climate (MeteoSwiss) at Wynau (5 km from Oensingen) and Sion. Because of the large differences in the estimated rooting depth, which may render the interpretation of the results more difficult, simulations were carried out assuming for both sites either 800 mm (subsequently denoted as “deep”) or 130 mm (subsequently denoted as “shallow”).

The same management was prescribed for both sites each year, with 5 cuts between May 5 and October 25, and applications of about 240kg/ha of nitrogen fertilizers (190 kgN/ha in mineral form, 50 kgN/ha in organic form). This reflects the intensive management at Oensingen [Fig. 2b-c in Ammann et al., 2009].

Atmospheric CO₂ concentrations were assumed constant at 370 ppm. Initial conditions for root and shoot mass and soil organic matter were specified according to field data from Oensingen. Additional equilibrium simulations for Sion spanning a total of about 1000 years showed that near-steady-state conditions were reached after 5 years. Therefore the first 5 years of each simulation were omitted from the analysis.

4. RESULTS

First we characterize the water supply and demand and consequently the water deficiency at both sites, partly due to climate and partly due to soil conditions. Then we quantify the minimum water amount required to meet the demand and to sustain potential productivity across pedo-climatic conditions. These water amounts are finally analyzed in relation to key variables.

4.1 Climate, evapotranspiration efficiency and water requirements

Basic features relative to climate, drought stress and water requirements at Oensingen and Sion are presented in Figure 2. Note that all values are computed over the period March 1 to October 31, which is assumed to represent the growing season.

Average growing-season precipitation at Oensingen (800 mm) is twice the amount of that at Sion (400mm), but water demand for potential growth at Oensingen is on average only about 70 % of the value estimated for Sion. As a result, ET efficiency is of the order of 0.9 (deep) or 0.7 (shallow) at Oensingen, but only of the order of 0.6 (deep) and 0.5 (shallow) at Sion.

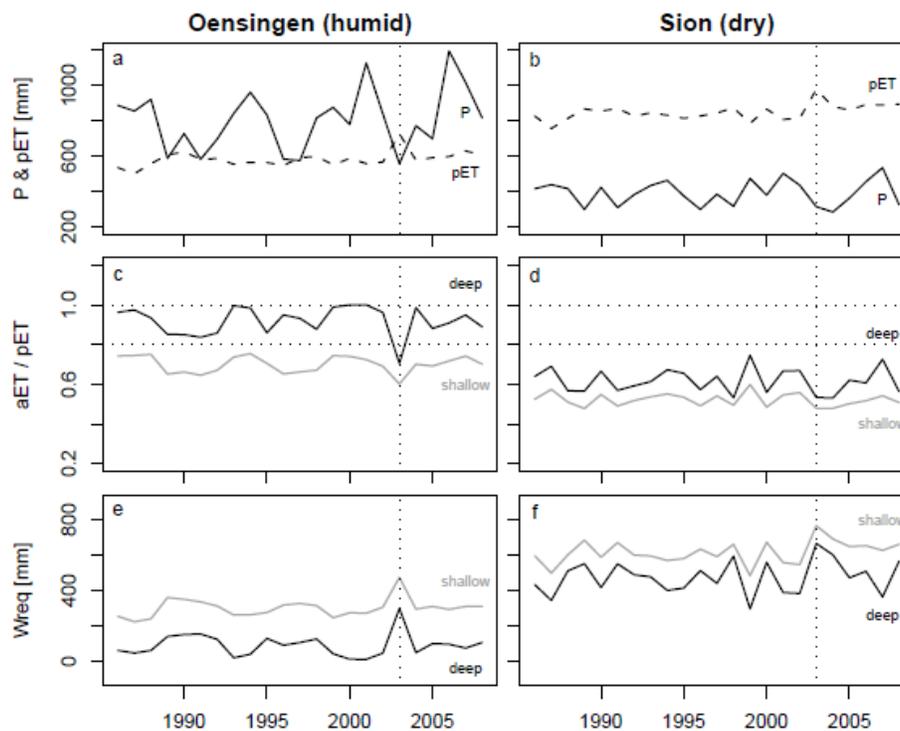


Figure 2 – Precipitation (solid lines) and pET (dashed lines) (a-b), actual to potential ET ratio (c-d) and water requirement (e-f) for Oensingen (left) and Sion (right) over 1986-2008. Values were summed over the growing season from March to October. Dotted lines indicate the 0.8 common ET ratio reference and maximum at 1, and year 2003. Black lines indicate the runs using a deep soil (800 mm), and gray lines that using a shallow soil (130 mm).

2003 is the only year where ET efficiency falls below 0.8 (the common ET ratio reference [Doorenbos & Kassam, 1979]) in deep rooting conditions at Oensingen, due to an increase in pET rather than a drop in aET. It is also the only year where pET exceeds precipitation, whereas this is the case every year at Sion, leading at this site to semi-arid growing conditions. Low precipitation, low relative humidity, high wind speed and high radiation typical for the Rhone Valley are responsible for the large gap between the low water availability and high water demand.

The amounts of water required to fill this gap along over the growing season are shown in Figure 2e-f. Average needs are 90 mm for a deep soil at Oensingen, with a peak of 300 mm during the summer of 2003. Average requirements in the case of a shallow soil are about 300 mm at this site. At Sion, average water requirements are of the order of 400 mm (deep) or 600 mm (shallow), with variations of about 50 to 100 mm from year to year and peak requirements close to 800 mm.

4.2 Soil properties and water losses

Shallow soils increase drought stress and water requirements (gray lines in Fig. 2c-f) for unchanged precipitation and pET, in a larger proportion at Oensingen than at Sion. Simulations with PROGRASS suggest that water requirements are not simply given by the difference between growing-season pET and precipitation. Losses from surface runoff and drainage limit the precipitation efficiency in meeting plant demand, in particular in the case of high precipitation amounts and/or shallow soils (i.e. limited holding and infiltration capacity). This is the case at Oensingen (and Sion, in the simulation with a shallow soil only), where losses account for about 50% of the seasonal rainfall.

4.3 Irrigation demand as a function of water deficiency

Because of the considerable variability in climate (20 % in P and 6 % in pET) and water requirements, it is interesting from a practical point of view to find simple relations for expressing water requirements as a function of selected key variables. As shown in Fig. 3a, water requirements can, for instance, be expressed as a decreasing function of the so-called atmospheric water budget (the difference between precipitation and pET). There is an asymptotic behaviour for positive values of $P - pET$, with limits depending on assumed soil depth. Even simpler is the relation between water requirements and the difference between pET and aET (Fig. 3b), which is, by construction, not surprising at the hourly time step but could have integrated non-linearities on the growing season scale. Note, however, the systematic departure from the 1:1-line, with Wreq in excess of $pET - aET$, indicative of the fact that aET is also sustained by capillary rise (about 200 mm per growing season at Sion when a shallow soil is assumed).

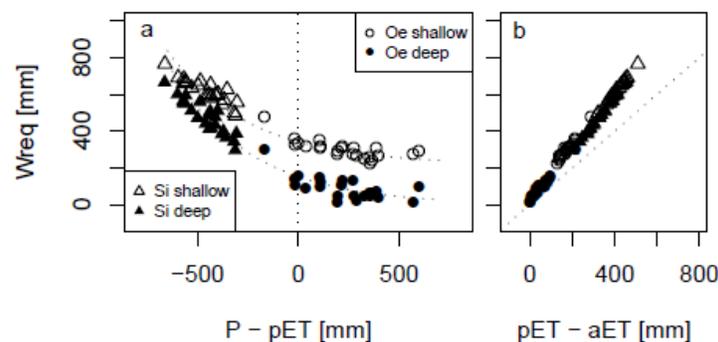


Figure 3 – Water requirement expressed as a function of the so-called atmospheric budget (precipitation minus pET) (a) and of the difference between pET and aET (b). Oensingen is represented with circles and Sion with triangles. Full/empty symbols refer to results of simulations for a deep/shallow soil.

4.4 Irrigation demand and productivity

From an agronomic perspective it is interesting to examine drought stress and water requirements in relation to productivity. Yield stability is one of the main purposes of irrigation. The absolute gain in productivity as a function of the water requirements is shown in Figure 4a. Expressed as a function of relative ET (or ET efficiency), relative productivity appears to follow a linear relationship (Fig. 4b). A one-to-one relationship is the expected behaviour for a constant water use efficiency, but the simulations suggests that relative yield is generally below relative ET, except in the case of very humid climates and deep soils. Water use efficiency is found to decrease with increasing soil shallowness and climate aridity, so does the yield gain by unit of irrigation water required (Fig. 4a). In any case, once the potential productivity is reached (of the order of 15-16 t/ha/y at the two study sites) no further benefits can be expected from an increase in irrigation.

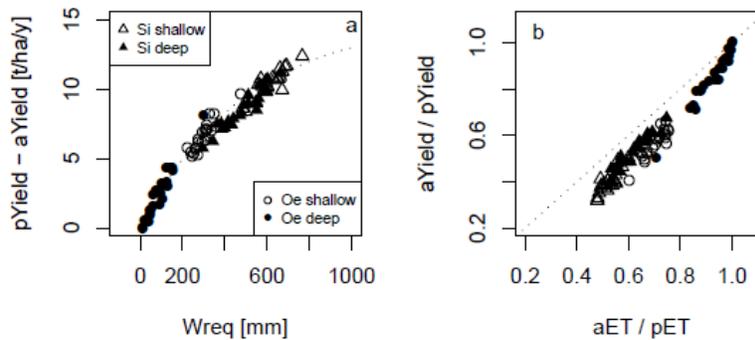


Figure 4 – Absolute yield gains as function of the water requirements (a) and relative productivity as a function of relative ET (b).

5. SYNTHESIS AND DISCUSSION

In this paper we presented an estimation of irrigation water requirements in managed grasslands relying on simulations with a process-based ecosystem model. We studied two sites with contrasting climates and soils, Oensingen being characterized by radiation-limited and Sion by soil moisture-limited growing conditions [Seneviratne et al., 2010].

The results suggest that under current climatic conditions, precipitation is a key variable, both in relation to the average requirements as well as to variability. In humid climates, however, soil properties and rooting depths can also play a role, because in shallow soils with limited storage and infiltration capacity a large fraction of the precipitation is lost as surface runoff and drainage, eventually leading to significant soil water deficits. In shallow soil capillary rise from the water table can nevertheless partially compensate for water deficits. In general this shows the importance of a proper description, in ecosystem models, of water fluxes at the rooting zone lower boundary and of the plant rooting strategy under drought stress [Teuling et al., 2006].

Under a future climate involving a possible increase in the intensity of precipitation events, the partitioning of water fluxes into consumption by the grassland ET and losses by runoff and drainage may change towards generating higher drought stress in the intervals. Plant growth can temporarily suffer from anaerobic conditions due to soil moisture exceeding field capacity, which already occur in winter in Oensingen.

In spite of variability across sites and in time, we found that water requirements can easily be understood and estimated using simple relations. For instance we showed how water requirements can be expressed as a function of the so-called atmospheric water budget. The asymptotic behaviour found in our simulations is reminiscent of the relations of seasonal mean fluxes discussed in Budyko [1974]. In particular, the fact that the limiting value depends on soil depth can be well understood in the context of analysis of the seasonal water balance of terrestrial ecosystems developed by Milly [1993].

We also found a linear relationship between relative productivity (or yield) and relative ET, which appears to support the simple productivity model at the base of the Food and Agriculture Organisation (FAO) methodology [Doorenbos & Kassam, 1979]. We expect that such relations can be generalized to other sites, providing guidance for practitioners. But care is needed in doing so, because important aspects were not yet investigated, e.g. situations where water is lost by lateral fluxes driven by topography, when the rooting zone is not in contact with the water table, or when soil and canopy characteristics are affected by management.

Grassland management includes fertilization (which affects potential productivity and pET), cutting regime (which also has implications for both), grazing (seen as a disturbance but also in relation to soil compaction), rotations and the like. Models that are able to account for some if not all of these aspects, as it is the case with PROGRASS, are therefore needed to study the system sensitivity to drought stress and irrigation. This type of model also provides opportunities to study water requirements for specific growth phases, rather than for the whole growing season as presented here. This could be important, for instance, in view of the necessity to optimize water use in irrigation.

Finally, we would like to point out that the present estimates should in any case be considered as a lower bound, because we implicitly assumed a perfect drought stress monitoring and full efficiency with respect to irrigation. In practice, irrigation efficiency depends on local conditions (including soil permeability) as well as various technological aspects (frequency, amount and position), which need to be considered in practical applications. The target yield and related soil moisture threshold for estimating water requirements (currently aiming at zero stress) should in the end be adjusted to account for economical and environmental factors shifting the optimum irrigation level.

6. CONCLUSION AND OUTLOOK

In this study we were able to highlight some of the key features of the relation between water requirements, climate and soil. We limited our attention to current climatic conditions, and showed that even in humid climates irrigation need could be quite substantial in the presence of shallow soils. The model produces daily estimates and is able to consider the interactive effects of management intensity and water deficiency.

The study is part of the ACQWA European project, which is currently being carried out to estimate climate change impacts on water quantity and quality in vulnerable mountain catchments. Next steps towards reaching the aims of this project include revising PROGRASS to allow simulating grassland productivity and water needs along an altitudinal gradient. This implies extensions of the model towards accounting for snow cover, slope (lateral fluxes), heterogeneous and stone-rich soils. Note that in mountain regions grasslands are often used as pastures, and thus the model needs to be adapted to include the impacts of grazing. For model development and testing, input and verification data are essential. Networks of field experiments make data available for this purpose [Calame et al., 1992; Jeangros et al., 1992; Jonas et al., 2008].

Aiming at producing Canton-scale estimates of future water requirements, the modelling approach will also be made spatially explicit and extended to the other relevant crops (such as, maize, wheat, fruit trees and grapevine), cultivated in the lower elevation belt of the Rhone catchment. Climate and hydrological change scenarios downscaled to the alpine region will be used to drive future conditions for agricultural production. Comparison of results with those obtained with the FAO CROPWAT methodology or Fuhrer & Jasper [2009] for instance will help estimate the uncertainty associated with model predictions.

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