Field Crops Research 211 (2017) 48–65

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

# Crop water use under Swiss pedoclimatic conditions – Evaluation of lysimeter data covering a seven-year period

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ARTICLE INFO

*Keywords:*
Crop coefficient
Evapotranspiration
Lysimeter
Phenology
Water use efficiency

ABSTRACT

Due to climate change, agricultural production in Europe will be challenged by higher temperatures and shifts in precipitation distribution that will give rise to frequent summer droughts. An adaptation of agricultural systems to these changes requires detailed knowledge of crop water use characteristics. This study aimed to evaluate the dynamics of evapotranspiration and water uptake in different crops under the typical edaphoclimatic conditions of Switzerland. Seven years (2009–2015) of high resolution lysimeter mass data including 70 lysimeter-by-year combinations were evaluated. The "adaptive window and adaptive threshold "-filter (AWAT) was used to determine evapotranspiration (ET), precipitation (P), crop coefficient ($K_c$) and water use efficiency (WUE). Additionally, FDR sensors installed in the lysimeter soil core allowed recording the temporal dynamic of soil water extraction. The evaluation comprised grain maize, silage maize, rapeseed, sugar beets, winter barley, winter wheat and temporary ley. The AWAT filter was successfully used to determine lysimeter P that was inserted in the lysimeter water balance equation to calculate daily ET. It could be shown that the peak of daily crop coefficient coincided with the time of flowering for all flowering arable crops. WUE's lay in the range given by standard literature, but daily crop coefficients were clearly higher than proposed by the Food and Agriculture Organization of the United Nations (FAO) which is partially due to an oasis and border effect of the lysimeters. Years with limited water availability were characterized by a comparably low $K_c$. For example, rapeseed in 2011 and maize in 2015 showed substantially lower $K_c$ values. In accordance with the reduced $K_c$, readily available water was totally removed down to soil depth of at minimum 0.85 m. The limited water availability led to significantly lower yields only in case of silage maize in 2015. These results show overall current water supply to be sufficient under Swiss conditions; however, if drought events like in 2015 become more frequent and even more intense, yield potential of typical Swiss arable crops will be limited by water availability.

## 1. Introduction

Agricultural production is strongly related to climatic conditions throughout the vegetation period. Especially, water availability and temperature are crucial parameters that determine crop development and yield. It is predicted that temperatures will rise, rainfall distribution will change and the frequency of droughts will increase in Europe as a result of global climate change (Lehner et al., 2006). Swiss agriculture will increasingly be challenged by water shortages in summer seasons due to shifts in precipitation distribution (Calanca, 2007). An adaptation to climate change requires detailed information about future climate conditions and their effects on crop growth. The performance of crops in changing climate conditions follows complex interaction patterns making predictions difficult (Porter and Semenov, 2005). Nevertheless, several promising approaches have been made in modelling arable cropping under temperate climate conditions of central Europe (Calanca et al., 2016; Holzkämper et al., 2013; Holzkämper et al., 2015; Woli et al., 2012). As a basis for such modeling approaches, actual crop performance has to be characterized in detail. Important input factors for such models are temperature and water availability. Of these two factors water availability is the more dynamic and complex one. The total amount of potential plant available water depends on soil type (especially pore volume) and rooting depth. The amount of plant-available water in a certain period of time during the growing season is mainly determined by specific evapotranspiration rates and precipitation amounts. Both rely on the predominating weather conditions. Therefore, a long-term continuous monitoring of crop evapotranspiration (ET) and precipitation (P) is necessary to characterize crop water use and to detect the conditions under which water availability is probably insufficient. To assess the dynamics of crop water use,

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http://dx.doi.org/10.1016/j.fcr.2017.06.003
Received 14 February 2017; Received in revised form 2 June 2017; Accepted 5 June 2017

lysimeters are the most precise means providing data in high temporal resolution under natural weather conditions (Fank, 2013; Goss and Ehlers, 2009; Seneviratne et al., 2012).

Modern high-precision lysimeters can be used to study groundwater recharge and dissolved substances in the seepage water as well as water fluxes in the soil/plant-atmosphere interface (Gebler et al., 2015; Robison et al., 2004). The modern weighing systems are sensitive enough to detect even dew fall, fog and rime as P (Meissner et al., 2007). However, the data evaluation of high-resolution lysimeters is challenging. The basic challenge is that lysimeter balances do not only record mass changes caused by water in- and outflow but also noise. Such noise can be due to wind, field work, little animals (mice or birds), balance errors or handling of measurement devices and provoke noisy vibrations and hence mass changes (Hannes et al., 2015). The noise leads to an error accumulation when aggregating measured water fluxes (ET and P) and results in a large overestimation of both fluxes (Fank, 2013). Recent approaches to tackle this problem for high resolution mass data were moving averages within a certain time window (Nolz et al., 2013). A method that adapts the moving average to noise severity was suggested by Peters et al. (2014) and yielded good accuracy for data with high temporal resolution (Hannes et al., 2015).

The reference evapotranspiration ($ET_0$) is a globally used concept that describes potential ET and characterizes the climatic conditions at a specific location (Allen, 1998). The most sophisticated approach was provided by the Food and Agriculture Organization of the United Nations (FAO) and requires detailed meteorological input data for $ET_0$ calculation (Allen, 1998). Less demanding approaches were developed on a more empirical basis (Priestley and Taylor, 1972; Primault, 1981; Turc, 1961). They are commonly used for irrigation management and climate modelling. The concept of reference evapotranspiration is also used to assess the effects of climate change (Calanca et al., 2011; Fuhrer and Jasper, 2009; Holzkämper et al., 2013; Holzkämper et al., 2015) and to calculate drought indices such as the agricultural reference index for drought (Woli et al., 2012). $ET_0$ can be linked to ET of a certain crop by introducing a specific crop coefficient ($K_c$) as it is proposed by Allen (1998). $K_c$ is the ratio of the actual measured crop evapotranspiration ($ET_a$) to $ET_0$.

Crop ET is a function of green leaf area. The growth of photosynthetic active leaf area and crop phenology has a parallel development. Looking in more detail at the temporal evolution of crop ET, stage of flowering might play a key role in crop water balance. In grain crops, it is broadly investigated that drought stress occurring during stage of flowering causes high yield reduction whereas drought stress during vegetative growing phases causes, relatively seen, less yield loss (Barnabas et al., 2008; Saini and Westgate, 2000). The main possible effects are pollen sterility, failure of pollination, spikelet death or zygotic abortion (Saini and Westgate, 2000). Crop vulnerability to drought stress during flowering stage was observed in rapeseed (Istanbulluoglu et al., 2010), maize (Farre and Faci, 2009; Igbadun et al., 2007; Paredes et al., 2014), barley and wheat (reviewed in Barnabas et al., 2008).

Under natural environmental conditions, measurements of daily ET rates require modern technical devices as precision lysimeters, eddy covariance (Yang et al., 2014a) or remote sensing technologies (Yang et al., 2014b). Several studies using one of these three technologies investigated the course of ET or daily $K_c$ values in dependence of phenological stages (Chattaraj et al., 2013; Irmak et al., 2015; Ko et al., 2009; Piccinni et al., 2009). None of these studies analyzed large enough data sets that would allow for statistical testing. Nevertheless, in winter wheat maximal crop coefficients were observed in the window around flowering, i.e. between heading (Ko et al., 2009), flowering (Irmak et al., 2015) and the milking stage (Chattaraj et al., 2013). For maize, highest crop coefficients were observed during milking stage (Piccinni et al., 2009). A broad study at field scale on the relationship between ET peak, maximal $K_c$ values and stage of flowering is still lacking.

Crop water use efficiency (WUE) is the most important parameter for improving the management of agricultural water resources (Tallec et al., 2013). In most agricultural studies, WUE is determined as total aboveground biomass production per amount of water used. To our knowledge, there is no information about WUE of different crops under central European conditions. With an increasing probability of summer droughts (Calanca, 2007), crop water uptake from subsoil will become more important (Gaiser et al., 2012; Kirkegaard et al., 2007). Such drought-tolerant crop cultivars require deep and efficient root systems to sustain drought periods without yield loss (Challinor et al., 2010; Debaeke and Aboudrare, 2004).

Hence, a better knowledge of the timing and depth of water extraction is important for decision making concerning the choice of suitable crops. Furthermore, the question to what extend deep soil water is tapped by a crop during dry periods and at critical stages of development is relevant for decision making in breeding programs (Araus et al., 2008). If deep soil water is not used during dry periods, selection may focus on drought avoidance by means of deeper rooting. In case water was extracted from the whole soil profile in the majority of years, the focus should be more on economizing water use. The evaluation of ET and soil water extraction depths can be provided by measurements in lysimeter studies.

The aim of the study was to characterize crop water use under Swiss climatic conditions with regard to the following questions: (i) which differences exist in the temporal development and amount of water uptake between the crops, (ii) how is water uptake related to crop phenology and (iii) which differences exist in the profile of water uptake between the cultivated crops.

To tackle these questions, seven years of data from a total of 12 large weighing lysimeters equipped with FDR sensors at 4 soil depths were evaluated using the temporal evolution of masses and water uptake in combination with weather data.

## 2. Methods

### 2.1. Lysimeter facility and measurement devices

The lysimeter facility of Agroscope Reckenholz was built in 2009

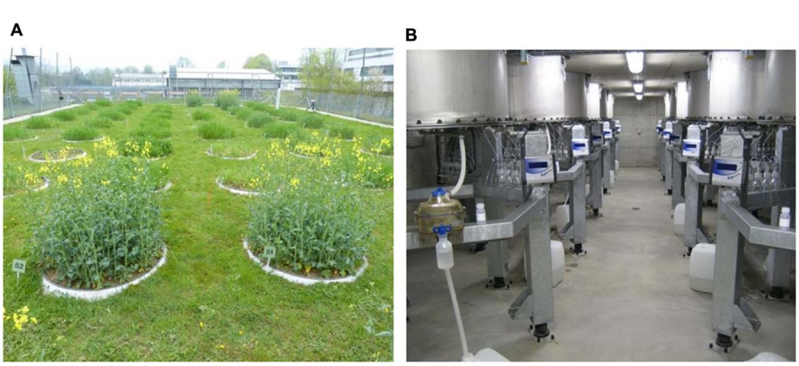


**Fig. 1.** Lysimeter facility from above in spring 2013 (left) and basement installations (right).