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Apparent steady state conditions in high resolution weighing-drainage lysimeters containing date palms grown under different salinities

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ABSTRACT

This study presents a novel investigation of long-term apparent steady state conditions under a prescribed leaching fraction criterion. The research was carried out during a 7-year investigation of date palm (*Phoenix dactylifera* L., cv. Medjool) trees exposed to elevated levels of irrigation water salinity. High resolution weighing lysimeters were designed and constructed to generate an accuracy of ±0.0075 mm. The lysimeters were equipped with precision flux data acquisition that measured the oscillations of their daily water storage difference (ΔW) and evapotranspiration. The leaching fraction was kept constant throughout the study.

The results generally confirmed that the assumption of apparent steady state conditions under the preprogrammed irrigation procedure was correct, even though inter- and intra-seasonal climate variations were observed. Measured ΔW oscillated slightly around zero even under high evapotranspiration demands. Drainage water electrical conductivity and leaching fraction were also found to stay fairly constant. The evapotranspiration of the date trees was found to be a function of the potential evapotranspiration, and rather insensitive to changes in the soil water storage (ΔW). Our analysis also indicates that for most practical purposes of monitoring and sustaining apparent steady state conditions, simple low-cost lysimeters, without weighing capability, can serve to monitor and sustain apparent steady state conditions, as long as there is water outflow from the lysimeters.

However, the high resolution (high cost) weighing lysimeters proved to be an efficient system for accurate data acquisition, which is necessary for accurate modeling. An annual numerical crop yield model, modified for a date palm field study, was successfully calibrated using data from a 2 month period, and subsequently validated against measured data from the following 8 months. The modified model closely predicted the daily oscillations of drainage water salinity and actual leaching fraction throughout the eight-month period.

1. Introduction

In most cases where crops are grown or investigated, both soil water salinity and water content (θ) vary in a spatial–temporal manner (Bresler and Hoffman, 1986; Bresler, 1977). An assumption of steady state conditions is often made in mathematical simulations of water uptake and plant growth. Bresler and Hoffman (1986) showed that experimental data from field plots was better described with a transient SPAC model rather than a steady-state solution. Letey (2007) and Letey and Feng (2007) questioned the steady-state assumption in spite of constant irrigation management over time.

Steady state conditions at a particular location occur if soil water content and solute concentrations, along with flow rates remain constant with time. Of course, such conditions do not actually occur in soil of commercially grown crops where wetting and drying processes are inherent (Letey et al., 2011). An apparent steady state condition (*ASSC*) can be defined for a system in which periodicity of boundary conditions, such as irrigation and potential evapotranspiration, exists. Under *ASSC*, the oscillations in plant–soil–water parameters (water content and salinity, for example) would have a frequency of $1/T$. For a system under such conditions the representative elementary time (*RET*) equals T such that:

$$\left.\frac{d\bar{\xi}(T)}{dt}\right|_{t\geq T} \approx 0 \quad (1)$$

Abbreviations: *ASSC*, apparent steady state conditions; *ET*, evapotranspiration; EC, electrical conductivity; ΔW, lysimeter daily change in water storage.

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where $\bar{\xi}$ is a representative character in the plant–soil–water system and t is the time. *ASSC* can be assumed within a time window of $t = T$.

Quasi steady state conditions have been observed previously in regularly irrigated annual crops (Rawlins, 1973; Bresler, 1977; Mmolawa and Or, 2000; Ben-Gal and Shani, 2003). However, in long-term studies (i.e., seasonal or multiple-year) of perennial crop response to elevated salinities, inter- and intra-seasonal differences in both soil salinity and water content are likely. It is therefore essential to carefully maintain pre-programmed soil water variables, in order to assure the steady-state conditions and hence to make the results valuable for agricultural management. Yet, documentation of an apparent steady state pattern in long-term response of plants to salinity studies, by means of weighing lysimeters, does not exist.

Investigations into the soil–plant–atmosphere continuum (SPAC) have facilitated development and calibration of numerical and analytical models. The response of crops to salinity is one of the input parameters for SPAC numerical models such as HYDRUS (Šimůnek et al., 1999), SOWACH (Dudley and Hanks, 1991; Dudley and Shani, 2003) and the Shani et al. (2007) analytical model ANSWER. Successful model execution obviously depends upon reliable input parameters obtained from well controlled and documented field or laboratory studies.

Lysimeters serve as tools for measuring one-dimensional water and ion balances (Van Bavel, 1961; Hillel et al., 1969). Despite several disadvantages inherent to lysimeters e.g., sidewall-boundary effects and microclimatic effects (Bergström, 1990; Flury et al., 1999; Corwin, 2000), they uniquely allow actual water and solute balance measurements under near-to-real field conditions. Lysimeters are therefore often used to assess environmental behavior of agrochemicals (Corwin et al., 1990, 1992; Vink et al., 1997; Schierholz et al., 2000) and to evaluate solute transport models and their parameters (Corwin et al., 1992; Klein et al., 1997; Vink et al., 1997; Butler et al., 1999). Lysimeters offer means for evapotranspiration (*ET*) – yield (*Y*) studies of crops subjected to a variety of environmental conditions, including: salinity, water (drought), irrigation frequency, nutrient level and specific ion toxicities (Bernstein and Francois, 1973; Shani and Dudley, 2001; Ben-Gal and Shani, 2002, 2003; Segal et al., 2006; Tripler et al., 2007, 2011). Weighing lysimeters additionally enable high temporal resolution (hours, days) quantification of *ET* rates. In the past 2 decades, vast advances have been achieved in lysimeter practice, with respect to internal structure, drainage water collection and weighing techniques. Lysimeters have therefore become increasingly useful for exploring temporal changes of soil water variables in investigations of plant response to environmental conditions. High accuracy weighing lysimeters can serve as tools for quantifying maintaining the pre-programmed apparent steady state conditions imperative in those studies. Lysimeters can also improve SPAC model simulations and predictions by trial and error adjustments of model parameters based on precise measurements of water flow within the lysimeter system (Skaggs et al., 2006). Lysimeters have yet to be utilized for documentation of apparent steady state patterns in studies of long-term response of plants to salinity.

We therefore hypothesized that high resolution weighing lysimeters equipped with an accurate system for measuring irrigation and drainage quantity and quality can monitor and quantify pre-programmed steady-state variables such as water storage and *LF* in salinity trials. They can also provide robust input data for models to improve calibration and increase simulation reliability. This study focused on the physical aspects of irrigation management in controlled studies of crop response to irrigation water salinity, and evaluated the assumed steady-state conditions. We used high resolution weighing lysimeters in order to address the following objectives: (1) to quantify the order of the deviation from steady-state of water storage and drainage water quality and quantity in a long-term salinity trial characterized by pre-programmed *LF* and irrigation water salinity; (2) to question whether or not fully equipped high resolution weighing lysimeter systems are more efficient than simple low-cost (non-weighing) systems in sustaining steady levels of soil water conditions; (3) to determine to what degree a numerical model, initially designed for annual crops and calibrated from the lysimeter system, is capable of describing soil water and solute fluxes for perennial crops.

2. Materials and methods

The experimental system utilized a field of lysimeters in which the response of date palm (*Phoenix dactylifera* L., cv. Medjool) to elevated levels of irrigation water salinity and boron was studied. Results from the system regarding evapotranspiration, biomass production and fruit yield can be found in two publications (Tripler et al., 2007, 2011).

2.1. Large-volume high-resolution weighing-drainage lysimeters

Each lysimeter (Fig. 1A) consisted of a PVC container filled with soil, a bottom layer of highly conductive porous media (rockwool) in contact with the soil, and drainage piping filled with the same material extending downward from the lysimeter bottom (Ben-Gal and Shani, 2002). The rockwool drainage extension disallowed saturation at the lower soil boundary while permitting water to move out of the soil and be collected. The lysimeter system included automatic water and fertilizer preparation and delivery, as described by Tripler et al. (2007). Individual lysimeters were positioned on square weighing platforms with load cells situated in each corner.

Over the course of our seven-year study of lysimeters planted with date palm trees, as the trees developed from seedlings to mature plants, their size, including their root systems, increased greatly. To sustain natural growth and avoid deterioration in root development or large oscillations in the daily change of water storage (ΔW) as the trees developed, the volume of all the containers was enlarged from 1 to 2.5 m^3 (1.4 m diameter and 1.7 m height) during the winter of 2003. Five lysimeters treated with EC of 1.8 $dS\,m^{-1}$ and five treated with 4 $dS\,m^{-1}$ were additionally increased to 10 m^3 (2.8 m diameter, 1.7 m height) during the winter of 2005. The winter season was chosen for tree transplanting in order to exploit relatively mild weather conditions and low *ET* rates. Modifications in the lysimeters involved increasing their root zone volume (1.5 m^3 in 2003 and 7.5 m^3 in 2005) with new, well-leached soil. The same *LF* and EC_d criteria were applied throughout the whole experimental period independently of the lysimeter size.

Fig. 1B shows a schematic diagram of the data acquisition and the electrical circuit for a single lysimeter. The temperature-compensated load cells (in the 10 m^3 lysimeters, model: H8C-N5-10K-6YB, Zemic Inc. and in the 2.5 m^3 lysimeters, model: 5123-D3-2.0t-20p1, Revere Transducers Inc.) were connected in parallel, supplied with an excitation voltage of 10 VDC, and had a maximum output of 30 ± 0.03 mV. The load cells' maximum weighing capacities were 8 and 36 tons in the 2.5 and 10 m^3 volume lysimeters, respectively. Practically, the significant range was the change in weight resulting from growth, the applied irrigation (*Ir*), and *ET*. The output current was therefore distributed across this relevant range of interest: a range of 14.4–18 tons translating to 12–15 mV was chosen for the 10 m^3 lysimeters and a range of 4–5 tons translating to 15–18.75 mV was selected for the