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Development of an innovative low cost weighing lysimeter for potted plants: Application in lysimetric stations

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ABSTRACT

For optimal, cost-saving management of irrigation water, precise knowledge is required of the overall water consumption made by the different species and varieties of plants existing in the area, under different conditions of climate, soil, etc. The most accurate way to determine this water consumption is by using weighing lysimeters. Unfortunately, because of current high costs, very few lysimetric stations are used in crop management to reveal real water consumption. Hence the need to develop new, low-cost lysimeters which make lysimetric stations available at an affordable price, and thus contribute to improve the management of water resources. This paper describes the development of a new, low-cost lysimeter, and its technical and economic valuation through the implementation of a 16-unit lysimetric station applied to analyse water consumption in potted plants. The system has been verified as highly accurate, easy to set up, and capable of filtering and storing data in real time, as well as controlling the electrovalves devised to open or close the tank where water drained from the pots is stored. This new agromotic system offers countless possibilities to accurately determine water consumption of any given plant. Additionally, if we consider its economic sustainability, proven by a study carried out for this specific purpose, which shows a positive net present value of the project, with a probability of 99%, it becomes a fascinating topic for research projects, as well as a highly recommended tool for crop productivity improvement.

1. Introduction

Among all the natural resources and inputs used in agriculture, water is probably the most determinant factor in crop productivity (Matson et al., 1997). In Mediterranean agriculture, with a semi-arid climate, the amount of water available in the soil is also the main limitation of a sustainable and economically viable agricultural production. In this context, irrigation scheduling is the most important factor affecting the quality and quantity of the harvests obtained. A bad management of irrigation can have serious environmental and socio-economic effects.

The first step to proper water management is to determine the irrigation requirements of each crop. To such an end it becomes necessary to have the techniques that allow both water inputs (rainfall and irrigation) and outputs (transpiration, evaporation and drainage) to be quantified in order to estimate the hydric balance. This balance is currently an approximate calculation based on soil sensors, agroclimatic stations and lysimeters (Allen et al., 1998). Soil moisture sensors used to determine water balances and to manage irrigation are usually rather inaccurate, since they only explore a small area, most of them are not calibrated for the type of soil on which they must be used and their implementation is full of problems caused by stones, underground cavities, etc. Therefore their readings, although quite close to real, are not altogether reliable. On the other hand, agroclimatic stations can be used to reveal evapotranspiration data of a reference crop (ETo) but in order to determine water consumption they need to be fed a number of crop coefficients which are specific for each variety, rootstock, soil, climate, etc. Although they do provide an orientation they fail to supply real information on each plant's water consumption. Because lysimeters can provide more exact values for each crop's water consumption, they are considered to be the standard method for direct measuring of evapotranspiration (Payero and Irmak, 2008). Agronomists have been using these devices, either individually or as part of lysimetric stations, to study the changes in weight experienced by a specific area within a cultivated plot. In its most general definition, a lysimeter is a mechanism used in agronomy to measure the volume of all the water going in and out of

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a receptacle containing an isolated mass of soil (Payero and Irmak, 2008). Therefore, several types of lysimeters can be differentiated depending on how they work and what they are used for, such as volumetric lysimeters, filling lysimeters and weighing lysimeters, among others, with the latter being the only ones that measure ET directly as a mass balance.

A weighing lysimeter typically consists of a large container filled with soil placed on a scale. The whole assembly is installed above an underground casket whose dimensions allow access to its interior for maintenance and calibration. Its surface is level with that of the surrounding soil, therefore undetectable to the naked eye, since it is covered by a plant crop. Many of these lysimeters are used to analyse crop evapotranspiration under different conditions (Liu et al., 2010; Zhang et al., 2007, 2008). Numerous limitations constrain these types of lysimeters: the construction work necessary for their installation are complex, their cost is high, they take up a large area, maintenance operations are complicated, they lack automation and their handling is restricted, to name but a few. All this restricts their use to research centres which, working from data obtained under very specific conditions, attempt to extrapolate these data so that farmers can use it as a guideline.

On the other hand, it is worth pointing out that crop yield and water consumption depend largely on the amount of solar radiation intercepted by the vegetable canopy. In crops with a degree of vegetable covering under 100%, the amount of light captured by the vegetation depends as much on plant development as on the branch-shaping system used and the design of the plantations. In addition, the physiological response of the plants, in particular the stomatal response, is also affected by environmental conditions, with a direct repercussion on the exchange of gases. On a daily basis, the levels of photosynthesis and perspiration and consequently the efficiency in the use of water, are not only a factor of the level of radiation intercepted but also dependent on the time of the day at which each level is reached. For example, Corelli (2003) demonstrated that photosynthesis in apple trees was less significant in the afternoon that in the morning, despite the fact that the levels of radiation intercepted at those times of the day were the same. This is because, generally speaking, both the temperature and the air vapour pressure deficits are higher in the morning than at midday or during the afternoon, which has a direct effect on the rate of water evaporation of the leaves. Therefore, contrary to what happens with low, dense cultivations such as garden grass, the tops of vineyards and fruit trees are less likely to form dense boundary layers of air that could reduce the volume of water perspired by the leaves (Jarvis, 1985).

In the case of trellised vineyards and espaliered orchards of fruit trees, mostly planted in rows with a North–South orientation, the level of radiation intercepted by the plants throughout the day can easily be modified by simply increasing or reducing the degree of inclination of the vegetation with regard to the direction of the incident radiation. In Mediterranean environments, characterized by dry, clear summers, a good deal of the incident radiation is direct, which justifies the adoption of these practices.

The initial hypothesis is that in vineyard plantations and espaliered fruit trees with a North–South orientation of the rows, the inclination of the vegetation to the West could increase the efficiency in the use of water, since it decreases the amount of radiation intercepted by the plant in the first hours of the afternoon, when the evaporative demand is higher than first thing in the morning. With the purpose of verifying this hypothesis in espaliered cultivations (e.g. vineyards) it is necessary to use an accurate system to measure all the variables that influence the hydric balance. The system chosen must also permit variations in the inclination of vegetation, arranging it as required by the tests being carried out.

This paper introduces a lysimeter capable of bypassing the inconveniences of the traditional models and of regulating the degree of inclination of the plant. This implies that (i) it is low cost, (ii) it is less bulky, (iii) it does not require building work and (iv) it may be used by farmers who are growing crops under their own specific conditions.

There are some lysimeters that meet a few of these requirements (Beeson Jr., 2011; Tripler et al., 2012; Wenting et al., 2013). In many cases, however, their structure is neither robust nor stable enough and their weighing method may be misleading, especially in the face of external weather phenomena such as strong gusts of wind (Howell et al., 1995). In other cases, automatic devices are not provided for measuring drainage. There is, therefore, plenty of room for improvement in this type of lysimeter, in terms of such factors as their structure and the design of the electronic system for automated measuring.

Additionally, this paper calculates whether the commercial development of the proposed lysimeter is economically viable. To this end, the so-called “Monte Carlo Simulation” (Dagpunar, 2007) has been chosen as a tool capable of supplying approximate solutions to mathematical problems by means of computerized pseudo-random number samplings.

2. Materials and methods

2.1. Mechanical design

Several prototypes were built before obtaining the unit described in this article. The first one consisted of a square support resting on a loadcell placed in a central position. The disadvantage of this design was that the object to be weighed had to be placed in the geometric centre of the support (which matches the centre of mass), otherwise the measurements given tended to be wrong, and the stability of the structure was awkward. Thus this design was incompatible with the deviations generated in the centre of mass due to the positioning of the trellis, the wind action and plant growth. A second prototype was then designed with two loadcells facing each other. This increased the admissible weight range up to 60 kg (2 × 30 kg), but it had the same problems as the previous one: lacking enough balance, its stability was jeopardized since the centre of mass must be located on the line joining the two load cells. The use of four load cells was discarded a priori due to the higher cost, difficulty to level the structure and the increase in the measurement error due to the use of a larger number of load cells.

The definitive prototype was finally developed with three cells (see Fig. 1), changing the square shape of the base into an equilateral triangle, arranging three cells in its respective apexes and a rigid structure that served as a support in order to anchor the lysimeter to the soil by using height-adjustable steel legs that guarantee horizontality of the platform. Also, a vertical structure made of aluminium profiles was inserted to support a trellis of 1.2 × 1 m, which can be inclined at different angles of up to 45° from the vertical axis. The design of the whole structure was made by SolidWorks. SolidWorks Simulation was used in the subsequent finite element deformation and stress analysis. The material used in the modelling was extruded aluminium with a yield strength of 1.45×10^8 N/m^2 and Young's modulus of 6.9×10^{10} N/m^2. The finite elements used were of solid, isotropic and linear type, resulting in a mesh with 52,756 high order quadratic elements (see Fig. 2). Wind loads used were those recommended by the Spanish Building Technical Code (CTE) considering the worst conditions (trellis at 90° with its entire surface covered by the plant). Vertical loads were determined by the maximum weight of the pot (600 N).

The bottom part of the lysimeter featured a surrounding hard plastic receptacle to collect the water percolated from the pot, and