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Root-soil interactions & adaptation strategies of plants in response to soil water availability

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***Abstract*—We study the *coupled action* of water uptake and root development of maize in potting soil under greenhouse conditions. To this end, we apply subsurface irrigation strategies that are constant over weeks. We perform synchronous real-time measurements of the co-evolving soil moisture fields and root distributions. Will constant irrigation regimes eventually lead to constant root distributions and soil moisture profiles? In this contribution we report on the preliminary results of a study on the soil-root system behavior and underlying feedback loops. Understanding of the feedback loops between the soil moisture distribution and root development opens new pathways for boosting natural adaptation and climate resilience of plants. We compare two soil-root-systems that differ in irrigation depth; one with a constant irrigation depth and one with a step wise increasing irrigation depth. We also compare a bare soil system without roots.**

***Index Terms*—root dynamics, soil moisture, water potential, feedback loops, steady states, complex systems**

I. INTRODUCTION

Climate change can have disastrous effects on agriculture [1]. Droughts will become more severe and last longer, resulting in increasing (water) stress on plants. However, research on crop management and yield improvement has largely focussed on controlled (green-house) environments with abundant available resources. Less research has been performed on optimizing the (long-term) yield under lack of resources. Furthermore, most studies focus on above ground control, whereas the underground control and plant root dynamics obtained less attention [2] [3]. This can be partly attributed to the intrinsic complexity of performing sub-surface measurements to quantify root dynamics.

However, the dynamic growth of plants - especially the flexibility of root growth - provides the plants (and us) with a strong ability to adapt and develop resilience to droughts and climate change. For instance, [3] concluded that a larger fine root density at depth in the soil increases yields by accessing extra resources. Deeper roots increases the water availability in the rootzone during droughts, which leads to higher resistance to subsequent droughts [4] [5]. Hence, the flexibility of the root system can be crucial for understanding the plants resilience and for manipulation of the natural adaptation strategies.

Root growth is a complex process and therefore difficult to model. Early studies on plant roots have simplified the task by concentrating on algorithms that largely disregard the dependency of root growth on conditions below the groundlevel or assuming constant and uniform soil conditions. Distinct relationships were derived for different classes of environments, biomes, soil types or climates. It has been found that, in most cases, the root distribution can be conveniently parameterized as an exponentially declining function with soil depth [6] [7] [8] [9] [10]. Such a distribution is often assumed in crop models. In less than optimum soil water conditions, however, different (opposite) distributions are found in nature [11] [12]. By altering irrigation schedules, [11] were able to stimulate a maximum root length density in cotton deeper in the soil. Also for other vegetation types it has been shown that parameters as root lengths, penetration depth and depletion rate at depth are influenced by soil moisture [13] [14].

Despite the recognition of the dependency of the root growth on soil moisture, quantitative relationships between these variables have scarcely been derived and included in crop models. Complications for deriving these relationships are (among other things) the large diversity of plant and root types (which requires many experiments to determine general relationships), the difficulty of highly controlled irrigation, and the challenge of measuring detailed soil moisture gradients and root development.

An exception is the model described by [15] that assumes a larger root density growth in the wetter regions of the soil where water is more easily available. The maximum rooting depth and the fraction of total dry matter partitioned to the roots, however, are treated as constants (i.e. independent of soil moisture) [15]. Data to verify the results of this model are limited.

From a system point of view, it is of great importance to understand whether the relationships between interdependent system variables result in positive or negative feedback loops because these determine if an initial change is amplified or dampened by the own action of the system. These loops inside the natural system can result in different states: states that are sensitive to external stimuli versus states that are self-sustaining and relatively insensitive to external changes [16]. Reasoned the other way around: the overall system behavior, studied under different external conditions and stimuli, can reveal important information about the underlying type of

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feedback loops and physical mechanisms. Understanding these loops opens new pathways for predicting system development, artificial manipulation and increased system control.

The current (ongoing) study builds further on the work of [15] and [17]. Eventually, we aim to verify the assumptions of [15] and to derive a qualitative dependency of the rooting density distribution and maximum rooting depth on the soil moisture (and water potential) profile. On top of that, we will also consider how the roots themselves simultaneously affect the soil moisture profile [17]. But, instead of a one-sided focus on how the soil hydraulic properties and soil moisture influences the plant root development [15] [17], or how the plant roots affect the soil water availability [18] [17] [18] [4] [5] and soil hydraulic properties [20], we explicitly want to know how these variables are reinforced or reversed by the *coupled action*. Conclusions will be drawn about (1) whether steady root distributions and soil moisture profiles evolve under steady irrigation and (2) the feedback mechanisms that underlie the long-term root development. With the obtained understanding, we aim to improve the modeling approach and performance of crop growth and land surface models.

II. METHODS

Most earlier studies on this topic concentrate on either (1) the influence of soil moisture on root dynamics (treating soil moisture as a constant driving factor), or (2) the influence of the root structure on the soil moisture patterns (assuming constant root architectures). In this study, however, neither the roots or the soil moisture distribution are taken as independent driver, but as system variables. This means that synchronous real-time measurements of the co-evolving soil moisture fields and root distributions are performed. Irrigation settings (quantities, depths and time-schedules), on the other hand, are implied as independent system drivers.

With modern techniques we aim to design a high precision subsurface irrigation regime that irrigates at various water depths with low and continuous flow rates, see figure 1 for the experimental set-up inside a rhizobox. Therefore, we make use of a porous dripline (4 mm diameter) and a peristaltic pump. Water can be supplied at five different levels. For surface irrigation, the top line is used. For subsurface irrigation, the irrigation depth is adjusted to the (observed) rooting depth.

We are interested in how the soil-root-system evolves in case of highly controlled constant irrigation conditions. To this end, different state-variables are monitored simultaneously (real-time). The opportunities for distributed monitoring are opening up with recent developments in miniaturizing low cost sensor technology (see https://www.tudelft.nl/2018/tu-delft/plantenna-op-weg-naar-een-internet-of-plants). The root evolution is recorded using video imagery. Considering how the root distribution and soil moisture conditions change in time and are correlated with eachother, will reveal important information about the feedback mechanisms that control the plant root development.

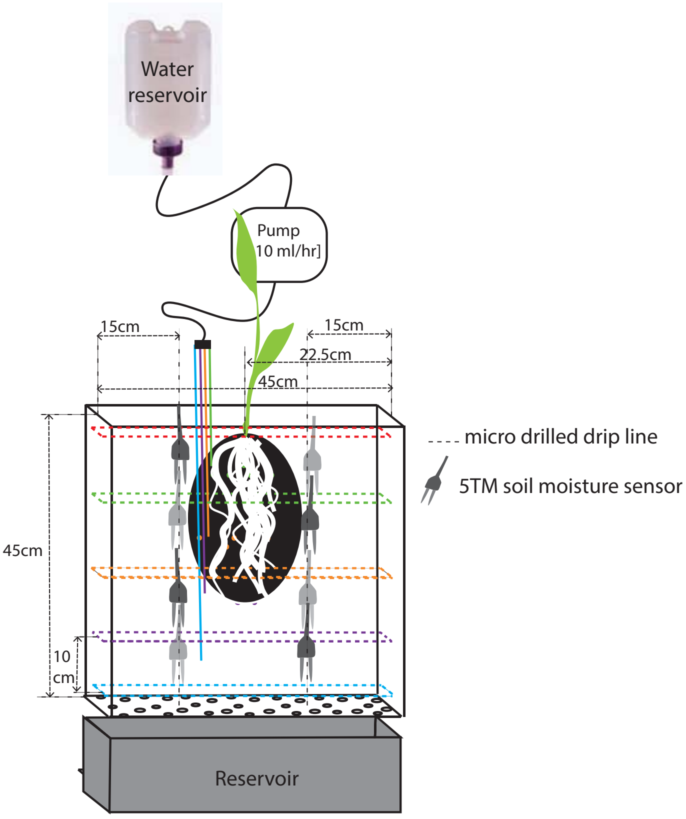

Fig. 1. Schematic representation of the experimental setup inside a rhizobox.

III. RESULTS

A. Point measurements and representativeness

Four different experiments were conducted inside a rhizobox: (1) bare soil with surface irrigation ($250ml/day$), (2) a surface irrigated plant with $250ml/day$, (3) a sub-surface irrigated plant with $250ml/day$, and (4) a surface irrigated plant with $16-32ml/day$. Water content was measured at four different positions in the box (covering a measuring area of about $1dm^3$), differing in depth and horizontal position (see the dark gray sensors in Fig.1). In experiments 1 and 4, water content was measured at six and eight (light gray sensors in Fig.1) locations respectively. The experiments with multiple sensors spread across the horizontal indicate that the evolution in the water content is not synchronous across the horizontal. However, the fashion in which the soil moisture rapidly increases when the water reaches the measuring area, and the way steady values can be approached (within a few days after the water has reached the measuring area), is rather similar over the horizontal (see Fig. 2).

B. Balances and steady states

In bare soil with surface irrigation, a constant soil moisture is eventually reached at each measuring point (Fig. 2). Both, the inflow from the top and the outflow from the bottom of the measuring area, are driven by the vertical gradient in the soil moisture. As long as the inflow is larger than the

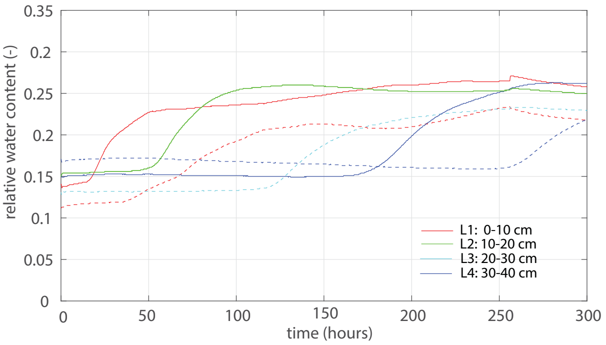

Fig. 2. Time series of the soil water content at six different positions in bare soil, under influence of surface irrigation of $250ml/day$. Solid (dashed) lines indicate postions at the right (left) side of the box, see figure 1.

outflow, the local water content increases, which increases the outflow and decreases the inflow (until the fluxes are in balance). Hence, the soil moisture is controlled by a negative (regulating) feedback loop. In the presence of a plant, an equilibrium state is reached in the upper two layers, but for lower values compared with the bare-soil situation (under equal irrigation scheme, Figs 2 and 3). This can be explained by the evapotranspiration, i.e. an extra outward water flux in the presence of plants. Another explanation could possibly be that the infiltration rate is larger when plants (and roots) are present. In the experiment with a plant, the lower layers do not reach an equilibrium state, see Fig 3.

C. Root growth

The results suggest that root growth is sensitive to the irrigation depth and soil moisture distribution. In case of surface irrigation, the gradient in the soil water content is initially upward oriented (largest values at the top of the soil). Eventually, however, the gradient turns over with largest water contents at the bottom. The turnover in the soil moisture gradient is caused by a smaller outflow from the bottom of the rhizobox compared with the flux through the soil (the air below the rhizobox does not suck-out the moisture as ground does). The evolution of the root growth corresponds well with the evolution of the soil moisture gradient. In the surface irrigation setting, the rooting depth initially lags behind the system with sub-surface irrigation (compare figures 3 and 4). However, eventually there is no clear difference in the rooting depth, possibly due to the unintended turnover of the soil moisture gradient and the thereafter similar downward gradient. A subsequent experiment with a smaller irrigation quantity shows a root system that remains limited to the first two layers of the rhizobox (also on the longer term), see Fig. 5.

IV. CONCLUSIONS AND OUTLOOK

The preliminary results suggest an influence of the irrigation depth and soil moisture profile on the rooting depth. This is in agreement with earlier studies. The results might also suggest a simultaneous effect of the roots on the soil moisture profiles: in the presence of plants, soil moisture tends to be smaller in the upper layers and eventually reach larger values in the lower layers, compared with bare soil (under equal irrigation settings). This might imply the existence of a positive feedback loop. More experiments will be performed to verify these results and for a further investigation of the soil-root-system behavior. However, even with highly controlled irrigation settings, it is difficult to control the vertical soil moisture profiles in bare soil. By using smaller irrigation quantities, the control on the soil moisture profiles was improved, but this possibly resulted in (unintended) water stress on the plant. Further improvements can possibly be made by improving the drainage at the bottom of the rhizobox.

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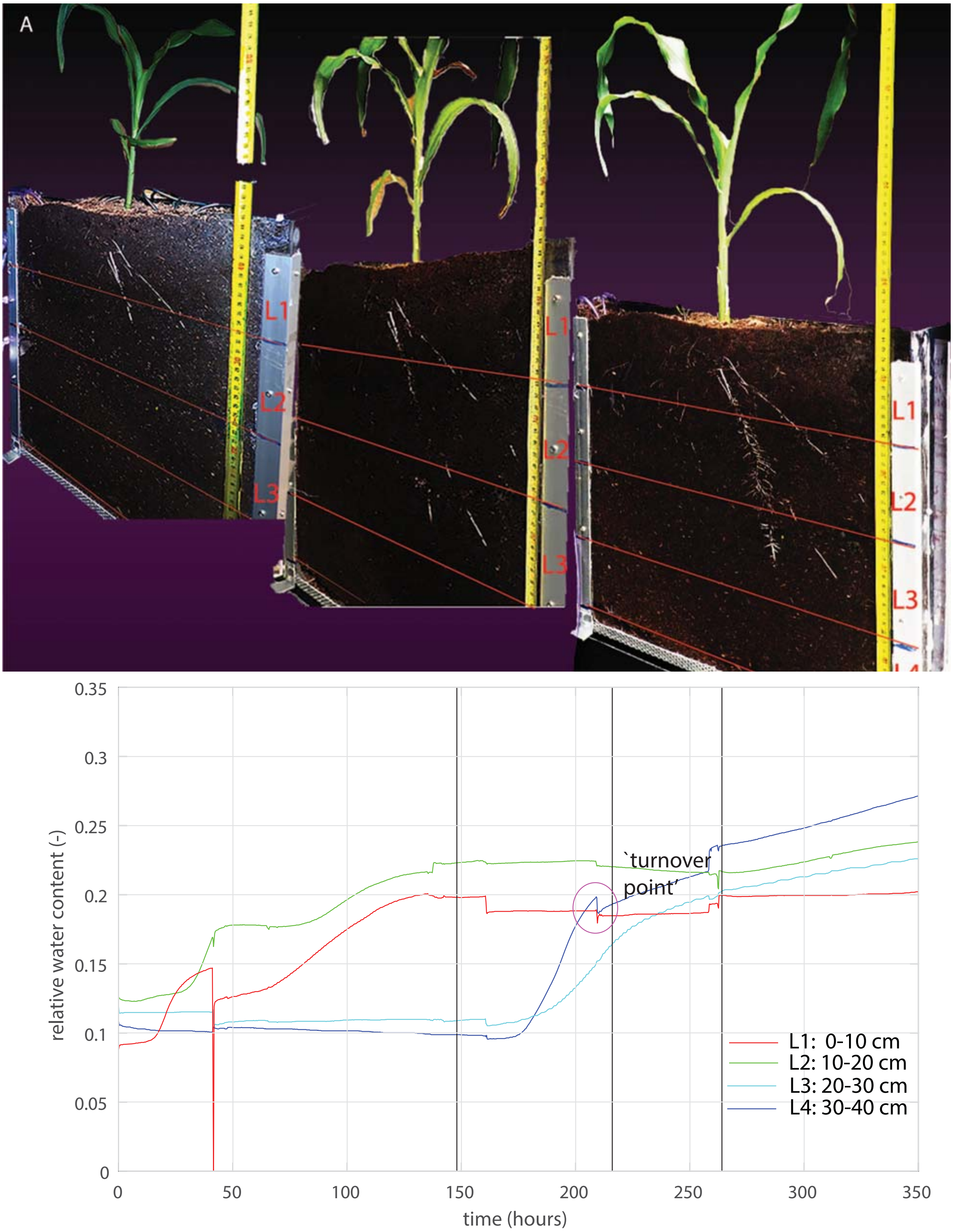

Fig. 3. Surface irrigation, $250ml/day$. (A) Photos of the roots at three different moments during the evolution. The moments of the photographs are indicated by vertical black lines in Panel B. (B) Time series of the soil water content at four different elevations.

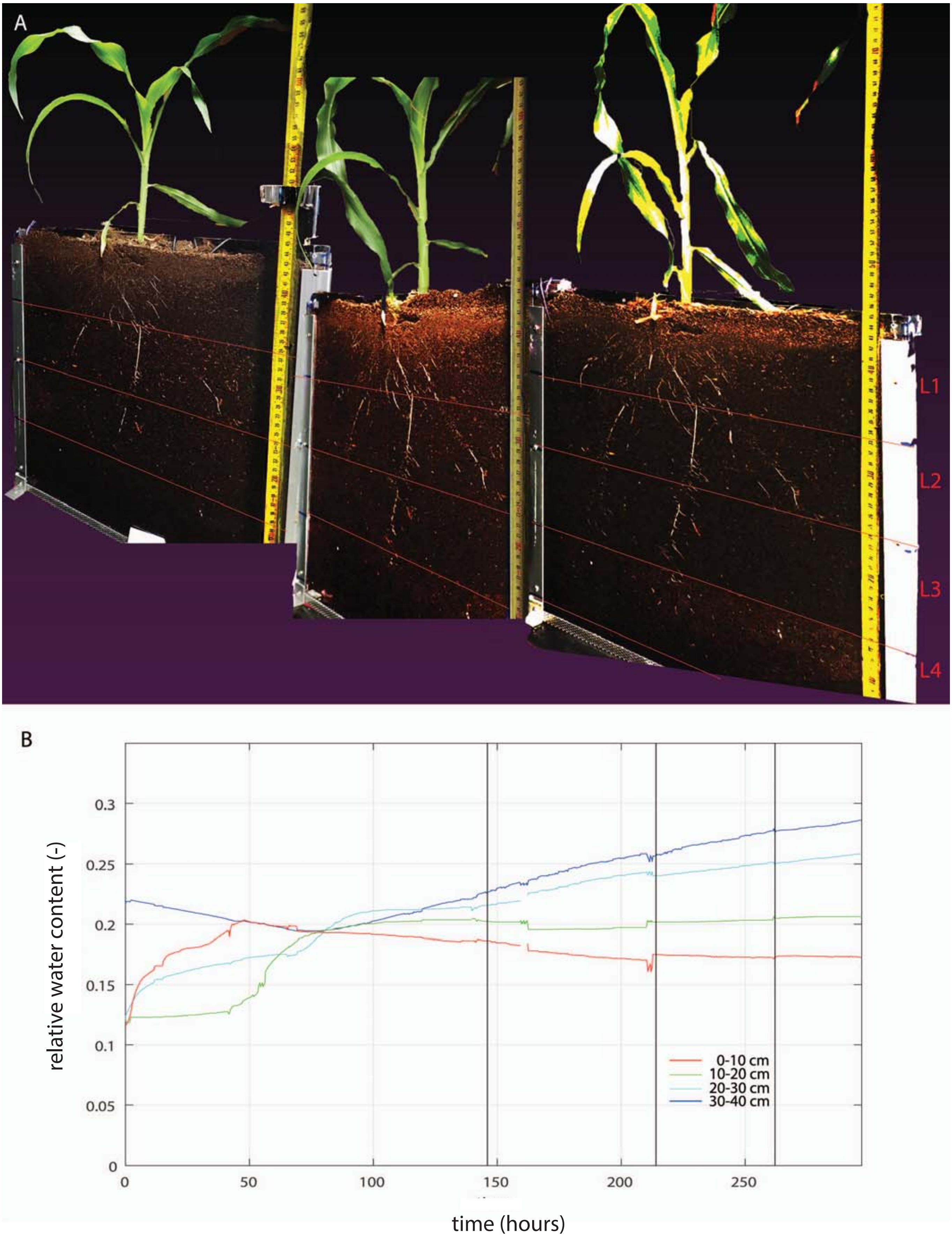

Fig. 4. Subsuface irrigation, $250ml/day$.(A) Photos of the roots at three different moments during the evolution. The moments of the photographs are indicated by black vertical lines in Panel B. (B) Timeseries of the soil water content at four different elevations. Around t=48, the soil in the top layer was disturbed (extra soil was added to fill the box).

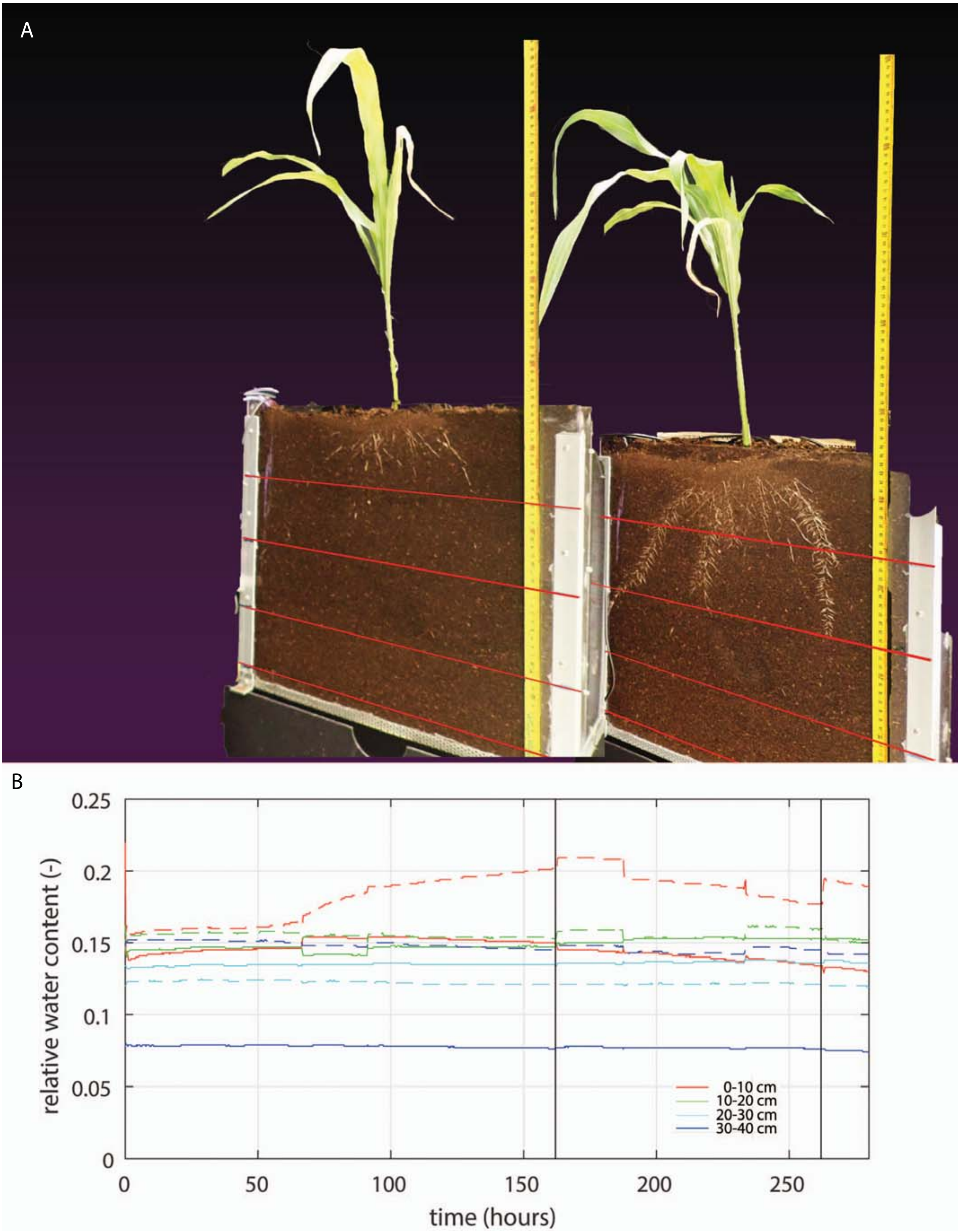

Fig. 5. Surface irrigation, $16 - 32ml/day$; the flow rate is adjusted a few times during the experiment to maintain low soil moisture. (A) Photos of the roots at two different moments during the evolution. The moments of the photographs are indicated by vertical black lines in Panel B. (B) Time series of the soil water content at eight different elevations. Solid (dashed) lines indicate positions at the right (left) side of the box, see figure 1.