Modelling minirhizotron observations to test experimental procedures

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Abstract

In order to help design experiments with minirhizotrons or interpret data from such experiments, a modelling approach is a valuable tool to complement empirical approaches. The general principle of this modelling approach is to calculate and to study the part of a theoretical root system that is intersected by passes through a virtual minirhizotron tube (modelled here as a cylinder). Various outputs can be calculated from this part of the root system, and related to the surrounding root system which is perfectly known, since it has been simulated and stored in a data structure. Therefore, the method involves two levels of modelling that are presented and discussed: the root system architecture of a crop, and the observations that can be achieved with minirhizotron tubes. Illustrations of the method are presented to study the effect of several factors on the rooting depth curves, and to show how images may be calculated to mimic what can actually be viewed from inside the tube. These first results show that the maximum rooting depth curves, as virtually observed in the minirhizotron tube, present large variations and strongly underestimate the maximum rooting depth of the modelled root system (up to 60 cm in average). The underestimation is still more critical when the radius of the tube is lower than 3 cm, and when the tube is close to the vertical (angle lower than 0.2 rad). The use of the 0.9 quantile instead of the average value, for each of the observation dates, leads to a better estimation of the maximum rooting depth.

Introduction

The minirhizotron technique is a very attractive means for studying various aspects of root dynamics in the field (Böhm, 1979; McMichael and Taylor, 1987). It consists of inserting transparent tubes into the soil, and monitoring root growth through these tubes, using a special optical device which is inserted into the tubes.

However, this method raises a number of questions (McMichael and Taylor, 1987). Firstly, sampling problems arise (number and location of the tubes, and tube inclination angles), mainly because the technique requires that only relatively small regions of the total volume be sampled if it is not to be too invasive. Secondly, the behaviour of roots growing in the soil medium is supposed to be represented by roots which are observed at the interface between the soil and the tube. For sampling, a number of strategic choices have to be made concerning the number, dimension, and positioning of the tubes, and these choices involve a large number of variables (e.g. distance from the plant or the row, location along the row, direction and inclination of the tube, and radius of the tube).

The optimal sampling design is therefore difficult to obtain in real world situations, and is highly dependent on the experimental conditions (e.g. type of crop, developmental stage, spatial arrangement of plants, and growth conditions) and on the specific objectives of the investigation. Addressing these questions experimentally generally represents a large amount of work, so that the experimental design is often decided according to a given background knowledge, which may be flawed with uncertainty and shortcomings.

The purpose of this paper is to show the potential power of simulation studies based on dynamic 3-dimensional theoretical architectures, for the design of a sampling scheme when planning new experi-
ments, and for the interpretation of data obtained by this minirhizotron technique. The principles of this method will be presented, together with some illustrative applications using a maize crop model, and dealing with different aspects that can be addressed by simulation. Although this study is particularly focused on the minirhizotron technique, it could easily be extended in order to consider other types of observations, such as those from the trench or auger techniques (Bengough et al., 1992; Grabarnik et al., 1996).

Methods

The modelling involves both a 3-dimensional representation of the root system architecture, and a model of the observations that are carried out with minirhizotrons.

Modelling the architecture of the root system

In this study, we used the model from Pagès et al. (1989) that is devoted to the simulation of maize crops. This model was chosen because it benefits from a large number of observations that were carried out throughout the world in recent years, and it was calibrated specifically from field data (Pagès and Pellerin, 1994; Pellerin and Pagès, 1994). Later, this model was evaluated by comparison of observed and simulated root maps (Pagès and Pellerin, 1996; Pellerin and Pagès, 1996). All parameters that were estimated in previous work are presented in Table 1 in Pagès and Pellerin (1996). The model simulates the three-dimensional architecture in discrete time steps. At each time step (1 day), the root system is extended by the application of three processes: (i) emission of new axile (seminal and nodal) roots from the shoot, (ii) growth, and (iii) branching. Root system development is related to cumulated temperatures with a base temperature of 6 °C. The root system is represented as a set of segments, each segment being the part of root that has been generated during one time step. For each segment, spatial coordinates of extreme points are stored, together with information on the position of the segment within the architecture (i.e. branching order, internode of origin, date of formation, and connections with other segments). Emission of new axile roots from the shoot is assumed to occur simultaneously for all roots from the same phytomer. The phytomer number on which emission takes place is calculated from a linear function of cumulated thermal units. The number of axile roots on each phytomer, as well as the angles for emission are fixed parameters. Roots are assumed to elongate according to a monomolecular growth function of thermal time,

\[ L = A(1 - e^{-bT}), \]

where \( L \) is length of the root; \( T \) is thermal time from emergence; \( A \) is final root length and \( b \) is a rate parameter. The asymptotic value \( A \) is drawn at random for each root at emergence, using estimated distributions. Growth directions are calculated by combining the effects of gravitropism and mechanical constraint, according to Pagès et al. (1989). Branching is assumed to occur after a constant time lag from initiation. Initiation is assumed to take place just behind the apex, with a density depending on the branching order. The branching direction is calculated using a branch angle drawn randomly from a normal distribution, and a radial angle drawn randomly from a uniform distribution over angles \( 0 - 2\pi \).

With the model, small crops were simulated at the 600 growing degree days (GDD) stage, each of them consisting of three rows of 17 plants, with the same within- and between-row spacings as in the field (15 cm within rows, 75 cm between rows). Only the central region of the crop (width: 45 cm, length 75 cm), representing a repetitive sub-unit containing 3 plants, was selected for the remainder of the study (Figure 1A). The size of the simulated crop (51 plants, 2.25 m x 2.55 m) was determined in order that all plants whose roots were likely to reach the selected zone were taken into account.

Modelling observations with minirhizotrons

Minirhizotrons allow different types of observations, that lead to different types of data acquisition (Maertens, 1987; McMichael and Taylor, 1987). Firstly, minirhizotrons may be used for the dynamic mapping of zones with roots and zones without roots. Evaluating rooting depth versus time is a classical example of this type of observation. The maximum rooting depth is an important variable that appears in several root and crop models (Penning de Vries et al., 1989). A refinement of the method is to quantify the root length density by counting the number of contacts between the roots and the tube. Although the potential use of minirhizotrons for quantifying root density variations is generally accepted, the level of precision that can be expected by the method is poorly understood and seems to depend on several experimental factors (Upchurch