Abstract

Correct evaluation of the root zone volume is essential to optimise crop water and nutrient management and to improve horticulture sustainability by reducing nitrogen non-point pollution and water use. A daily estimate of the root zone volume of row crops requires an evaluation of root elongation rate on three axes: depth, width between rows and length within row. Potato root growth rate was determined from data collected in the frame of the EU project FertOrgaNic from 2003 to 2005 in five experimental stations in Europe representative of most of the potato growing soil and climatic conditions. Because of the negligible level of growth limiting factors, typical of a fertigated cropping system, the simple algorithms proposed are based on cumulative thermal units (ΣThU) instead of a more complex carbon assimilation and partitioning approach. Algorithms fitted to the observed root elongation data were sufficiently precise to allow effective irrigation and fertigation management. Results from different soil and climatic conditions showed that root growth was maximum at 298 ΣThU (depth) and at 243 ΣThU (width). Root growth during the rapid growth stage in silty loam and loam soil ranged from 0.105 to 0.189 cm ΣThU⁻¹ while on loamy sand soils (83% coarse sand) reached 0.328 cm ΣThU⁻¹. Root growth was influenced by soil particle size distribution only where there was a marked difference in the soil structure (coarse sandy soil; sand > 70%). The proposed algorithms were implemented into the FertOrgaNic decision support system (DSS).

INTRODUCTION

Current cropping techniques pay little attention to the development of a plant’s roots. Moreover, models for management and prediction of nutrient use (Abrahamsen et al., 2000; Ahuja et al., 1999; Hanson et al., 1999) require, at the least, information about the depth of root growth. Most of these models derive rate of root growth from the total dry matter biomass, estimated on the basis of radiation interception and a generic partitioning coefficient. Furthermore, even the most complex management model outcome cannot go beyond the scientific stumbling block of the prevailing uncertainty about how to measure root biomass (Amato and Pardo, 1994) or the carbon lost through exudation from the root (Lamber, 1987). In applicative decision support systems (DSS), processes must be simplified in order to reduce the level of input. Such need leads to an estimation of the root zone volume that is often calculated as a linear function of the time elapsed since emergence (Borg and Grimes, 1986). The difficulty in correctly managing root development has led to oversimplifications that have often impaired the efficiency of
proposed DSS’s. Only recently have attempts been made to use algorithms relying on inputs feasibly obtainable in the field (Danuso et al., 1992; Nimah, 1996; Battilani et al., 1998, 1999, 2003a; Bussieres et al., 1999). A new approach to DSS modelling – which goes beyond the exclusively physical aspects (soil and climate) considered up to now – seems indispensable in order to effectively manage sustainable cropping techniques, addressing constraints such as increasingly limited water resources and the need to preserve soil from salinisation and losses in fertility. Furthermore the use of fertigation techniques coupled with drip irrigation offer the possibility to optimise the water and nutrient distribution over time (high frequency) and space (precise placement into the active root zone volume). Fertigation to improve both water and nutrient use efficiency requires a sufficiently precise calculation, at daily step, of the volume of soil colonised by active roots.

The objectives of this study, carried out within the framework of the EU project FertOrgaNic, were to assess fertigated root growth patterns and develop algorithms to implement into an applicative DSS.

MATERIALS AND METHODS

Root growth was measured from 2003 to 2005 at five experimental sites in Europe (Italy, Denmark, Slovakia, Czech Republic and Portugal). The soils, representative of most of the potato crop areas in Europe, ranged from coarse-sand to silty-loam. Treatments at each site were as follows: Non-Irrigated/Non-Fertilised control (NINF), Irrigated/Non-Fertilised (INF), Static fertigation and Dynamic fertigation. Details of the treatments and experimental design are reported in Battilani et al. (2008).

Soil particle size distribution, bulk density and moisture at field capacity and at permanent wilting point were measured every year. Soil hydraulic parameters were in the following range: bulk density 1.28-1.62 t m⁻³, field capacity 0.15-0.34 m³ m⁻³; wilting point 0.04-0.18 m³ m⁻³; saturation 0.31-0.44 m³ m⁻³.

Root growth was determined by destructive sampling. A trench was dug by hand from the base of potato plants to the adjoining row in two subplots at each experimental site. The trench was dug to 20 cm below the expected maximum root depth. Thus a profile wall was prepared. Active roots were gently teased out from the profile wall using a small trowel or a knife. Roots were followed till their end (root cap). Potato root growth was measured up to the maximum depth and width of the main active roots, defined as white, healthy roots with a diameter > 0.5 mm. Rooting depth (RZd m), width (RZW m) and length (RZl m) were measured at emergence and thereafter at approximately 15 to 30 day intervals until harvest or vegetative senescence and early tuber maturity. No relevant root growth was expected over the threshold of 50% of leaf senescence (at least 50% of the leaf lamina of a yellowish or brownish colour).

To normalize the effect of climatic differences between years and sites, data were plotted against the cumulated thermal units (ΣThU). Daily ΣThU was calculated from air temperature, recorded by a climatic station situated near the plots, following the method proposed by the Wisconsin University (2002).

Maximum root zone volume (RZ_VOL_MAX, m³) and maximum soil volume (SOIL_VOL_MAX, m³) were calculated as follows:

\[ RZ_{\text{VOL_MAX}} = RZ_d \times RZ_w \times RZ_l \]

\[ SOIL_{\text{VOL_MAX}} = RZ_d \times \text{Plant spacing} \]

where \( RZ_d \), \( RZ_w \) and \( RZ_l \) were the maximum rooting depth, width and length, respectively, recorded in the same year, site and treatment, and plant spacing was the product of the distance between rows (m) and plants within rows (m).

To avoid noise coming from both the variety and the different levels of soil fertility at each site, the observed data were expressed as relative \( RZ_i \) or \( RZW_i \) at day \( t \) calculated by dividing actual values of root zone depth or width at day \( t \) (i.e. \( RZ_t \)) by \( RZ_{\text{D_MAX}} \) or \( RZW_{\text{MAX}} \).

Results of root growth from this experiment were compared with model
simulations. Root development along the depth, width and length axes was simulated as a
dynamic response to the ΣThU (Battilani et al., 2003b, 2006) as follows:
\[
RZ_D = \min \left( 1, -0.811 + 1.814 / (1 + \exp(- (\SigmaThU - (-12.523))/53.665)) \right) RZ_{D,MAX}
\]
\[
RZ_W = \min \left( 1, -1.440 + 2.442 / (1 + \exp(- (\SigmaThU - (-31.655))/44.230)) \right) RZ_{W,MAX}
\]
\[
RZ_L = \left( \text{plant number per m row} \right)
\]
where \( RZ_{D,MAX} \) and \( RZ_{W,MAX} \) were the maximum expected root depth and width (m),
respectively. The root elongation on the \( RZ_L \) axes takes place mainly during shoot
development before emergence, thus the error considering \( RZ_L \) as a fixed value is
negligible. The Markvand model root growth algorithm (Plauborg et al., 1996) was found as
a reliable alternative to the aforesaid algorithms for soils with sand > 70%.

RESULTS AND DISCUSSION

For all the treatments the observed \( RZ_{D,MAX} \) ranged from 0.4 to 0.75 m, in absence
of limiting factors (e.g. saturated, anoxic soil layers or soil compaction), depending on
the variety, initial vigour of the mother tuber and favourable or unfavourable climate.
\( RZ_{D,MAX} \) was reached at 299.2 (± 24.8), 286.8 (± 40.5) and 298.9 (± 21.9) \( \SigmaThU \)
for NINF, INF and both fertigated treatments, respectively. \( RZ_{W,MAX} \) was reached at 233.0 (±
34.4), 211.3 (± 44.1) and 243.0 (± 27.7) \( \SigmaThU \) for NINF, INF and both fertigated
 treatments, respectively. Maximum \( RZ_L \) was reached in a very short time at the same
daily growth rate observed for \( RZ_{W,MAX} \). For this reason \( RZ_{MAX} \) was considered as
a fixed value equal to the distance between plants in the row. No difference was observed
between treatments. Major root development on both the depth and width axes was shown
to occur between emergence and the early tuberisation (about 30-35 d \(^1\)). Average root
growth on the depth and width axes during the rapid growth stage was 0.203 (± 0.05),
0.194 (± 0.04) and 0.206 (± 0.05) cm \( \text{ThU}^{-1} \) for NINF, INF and fertigated treatments,
respectively (Table 1). Static and Dynamic fertigation strategies had no influence on root
growth compared with the other treatments.

Root elongation was not influenced by soil texture. Root growth rate on silty loam
and loam soils (Italy and Czech Republic) ranged from 0.105 to 0.189 cm \( \text{ThU}^{-1} \) while on
loamy sand soil (83% coarse sand) in Denmark root growth rate reached 0.328 cm \( \text{ThU}^{-1} \).
Root growth rate on sandy loam soil in Poland (65% sand) was similar to that measured
in Italy and Czech Republic whereas in Portugal on sandy loam soil (78% sand) root growth rate was 0.321 cm \( \text{ThU}^{-1} \).

The effect of the soil temperature, estimated daily from the air temperature
(Plauborg, 2002), was negligible. In fact the crop is ridged to drain and warm up the soil
in the early growth stages when the plant is more sensitive to abiotic stresses like lack of
oxygen and low soil temperature. Soil temperature has a clear influence on the tuber
sprout and on the duration of the growth stage from planting to emergence. Before plant
emergence root growth is limited so the effect of low soil temperature was not significant.

Severe stresses in the early development stages do not affect initial root
development which is supported, at least for the first period, by the mother tuber’s
reserves. Static and Dynamic fertigation always maintained optimal water conditions and
nitrogen availability in the layer explored by roots. Furthermore, root growth patterns
with NINF and INF were similar to those measured with fertigation. Only small (not
significant) differences were observed with INF (Table 1, Fig. 1). As a consequence it
was not possible to establish a correlation between root elongation and residual soil
available water or soil nitrogen content.

The average \( RZ_{MAX, VOL} \) observed was 0.092 m\(^3\) per plant and the average ratio
\( RZ_{VOL,MAX}/SOIL_{VOL,MAX} \) was 0.74. These observations show that about one fourth of the
soil volume was not colonised by roots.

Examination of the root distribution along the growth axis of a ridged drip
irrigated potato crop showed that the solid that best fitted the root zone volume (\( RZ_{VOL} \))
was a paraboloid. As a result the general model describing \( RZ_{VOL} \) was:
\[
RZ_{VOL} = (0.667 RZ_W) (RZ_D/RZ_L)
\]

However, to calculate daily changes in \( RZ_{VOL} \), the observed development of \( RZ_D \),
RZ_W and RZ_L during the growing season must be substituted with biologically meaningful algorithms. Bivariate plots in Fig. 2 show a good agreement between simulated and observed root distribution irrespective of treatment despite a general overestimation of RZ_D and RZ_W (although INF was underestimated in Italy). Overestimation was caused by the slow root growth in Czechia up to about 600 ΣThU, and by data dispersion in the early stage, from 150 to 330 ΣThU, in Poland. In addition, simulation of root width lacked precision. Root width occurs in a very short time from late tuber sprout (before emergence) to the early stage of tuber formation. In such a short time several factors could affect root elongation on the width axes (for example water excess, mother tuber energy) resulting in more frequent “stop and go” not directly related to ΣThU, which is the algorithm’s driving force. As a consequence the data collected were more dispersed and outliers caused overestimation.

CONCLUSIONS

Plant’s root potential growth is set by genetics, but it is well known as well that root system formation proceeds in close coordination with shoot growth. Accordingly, root growth and its functions are regulated by the shoot through materials cycling between roots and shoots: in this way root growth responds to conditions of the soil environment and climatic demands imposed on the whole plant (Weaver and Bruner, 1927; Zobel, 1992). Fertigation management is aimed to ensure a source/sink ratio of physiological resources favourable to the storage organs while deficiencies in water and nutrient supply can increase their below-ground allocation (Brouwer and deWit, 1969).

To reach that goal fertigation supplies must be focused on optimal water and nutrient balance in the active root/soil interface. Thus, effective fertigation requires a precise knowledge about the volume of soil wetted by fertigation solution which considers the root zone volume at the moment of supply. The simple algorithms proposed to estimate root volume are based on cumulative thermal units, instead of a more complex approach based on carbon assimilation and partitioning. Owning to the negligible level of growth limiting factors, typical of a fertigated cropping system, the simple algorithms fitted with sufficient precision the observed root elongation. Such degree of precision is enough to allow an effective irrigation/fertigation management (Battilani et al., 2003a).

Results from different soil and climate conditions showed that root growth was maximum at 298 ΣThU (depth) and at 243 ΣThU (width). Root growth during the rapid growth stage on silty loam and loam soils ranged from 0.105 to 0.189 cm ThU^{-1} while on loamy sand soil reached 0.328 cm ThU^{-1}. Root growth was influenced by soil particle size distribution only where there was a marked difference in the soil structure (loamy sandy soil, sand >70%). The proposed algorithms are already implemented into the FertOrgaNic DSS. To enhance DSS’ precision a local calibration is suggested.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the EU Project FertOrgaNic Team.

Literature Cited


### Tables

Table 1. Average root growth rate (cm $\Sigma$ThU$^{-1}$) in Non Irrigated Non Fertilised (NINF), Irrigated Non Fertilised (INF) and Fertigated (Static, Dynamic) treatments.

<table>
<thead>
<tr>
<th>USDA texture class</th>
<th>Country</th>
<th>NINF</th>
<th>INF</th>
<th>Fertigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silty loam</td>
<td>Italy</td>
<td>0.105</td>
<td>0.189</td>
<td>0.108</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>Denmark</td>
<td>0.328</td>
<td>-</td>
<td>0.328</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>Poland</td>
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<td>0.159</td>
<td>0.166</td>
</tr>
<tr>
<td>Loam</td>
<td>Czech Rep.</td>
<td>0.106</td>
<td>0.106</td>
<td>0.106</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>Portugal</td>
<td>0.321</td>
<td>0.321</td>
<td>0.321</td>
</tr>
<tr>
<td>Overall average</td>
<td></td>
<td>0.203</td>
<td>0.194</td>
<td>0.206</td>
</tr>
</tbody>
</table>

### Figures

Fig. 1. Observed and simulated relative root growth along the depth and width axes in Non Irrigated Non Fertilised (NINF), Irrigated Non Fertilised (INF) and Fertigated (Static, Dynamic) treatments.
Fig. 2. Bivariate plots of observed and simulated relative root elongation (cm) along the depth and width axes in Non Irrigated Non Fertilised (NINF), Irrigated Non Fertilised (INF) and Fertigated (Static, Dynamic) treatments.