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To cite this version:

Benoit Gabrielle, Eric Justes, Pascal Denoroy. MODELLING OF TEMPERATURE AND NITROGEN EFFECTS ON THE ROOTING DYNAMICS OF WINTER OILSEED RAPE. 16th International Society of Soil Science Congress, Aug 1998, Montpellier, France. pp.230-T, 1998. <hal-00580710>

HAL Id: hal-00580710
https://hal.archives-ouvertes.fr/hal-00580710
Submitted on 29 Mar 2011

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MODELLING OF TEMPERATURE AND NITROGEN EFFECTS ON THE ROOTING DYNAMICS OF WINTER OILSEED RAPE
MODÉLISATION DES EFFETS DE LA TEMPÉRATURE ET DE LA FERTILISATION AZOTÉE SUR L’ENRACINEMENT DU COLZA D’HIVER

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Introduction

Recent concerns about the environmental impacts of arable crops as a consequence of intensive applications of fertiliser have fostered research on the processes of nutrient losses from soil/crop systems. Much attention has been devoted to nitrogen, because it is the major limiting element to crop growth, and also because it is potentially a threat to groundwater quality and of its involvement in global warming. Deterministic models simulating the water, carbon and N cycles within soils and crops provide unique tools to test different management scenarios at low cost (Shaffer et al., 1994). Within such models, the process of N uptake by crops contributes a major flux of N, making the prediction of crop uptake a major component in any one model.

Although the assimilation of soil mineral N by the roots is a rather complicated process, involving many controls and feedback loops depending on shoot status and conditions in the soil surrounding the roots (de Willigen and van Nordwijk, 1987), most models assume a single relationship between root uptake and mean soil nitrate, moisture content and root length density in a given soil layer (Watts and Hanks, 1978; Jones and Kiniry, 1986; Hansen et al., 1993; Lafolie, 1991). The root length density (RLD, cm roots cm⁻³ soil) is a macroscopic morphological factor allowing to upscale the microscopic ‘single root’ model which is usually employed to calculate the mass transport of nitrate from the bulk of the soil to the root, based on a Fick-like diffusion equation.

Along with the roots’ maximum rooting depth (MRD), RLD is then the main determinant of crop N uptake. Both MRD and RLD are known to be dependent on soil temperature and moisture content, and simple empirical relationships have been proposed to relate rooting depth to soil temperature sums and rooting density to rooting depth (Gerwitz and Page, 1974; Jones et al., 1991). However, relatively few pieces of work have been devoted to the test of these relationships in the field (Robertson et al., 1993; Savin et al., 1994), with none of them relating to winter rapeseed (Brassica napus, L.) to the best of our knowledge.

Here we used root mapping data obtained in a field trial involving different N fertiliser levels in Northern France to derive a sub-model for the rooting dynamics of rapeseed within the framework provided by the CERES models (Jones and Kiniry, 1986). The sub-model is then
implemented in a CERES model for rapeseed (Gabrielle et al., 1997), and its predictions of root growth are compared against field data.

Materials and Methods

Field data  Field data were collected within an intensive experiment aiming at directly assessing the seasonal dynamics of N in a soil cropped with rapeseed (variety Goéland) in the Champagne region in France (Cellier et al., 1997). The soil was a grey rendzina overlying a subsoil of compact chalk interspersed with vertical veins of gelifracted chalk. Three N treatments were setup on 30x30 m plots, with seasonal doses of 0, 135, and 270 kgN/ha for treatments N0, N1 and N2, respectively. Plots were sown in 0.29-m rows in late summer, 1994, and harvested in July the year after. For the in situ analysis of root growth, 4-m wide and 2.5-m deep trenches were dug once a month perpendicular to the rows, in which a vertical face was prepared using knives, brushes and small bellows to make the roots visible. The presence or absence of roots was then mapped through a 20-mm-grid mesh fixed on the face. This yielded the crops’ maximum rooting depth (in cm) for each treatment, but not directly the Root Length Density (RLD, cm roots cm$^{-3}$ soil) which was also of interest. However, we assumed the distribution of this variable to parallel that of the frequency of occupation we had measured over the profile, with an occupation of 100% corresponding to a maximum RLD value of 5 cm roots cm$^{-3}$ soil, as measured by Petersen et al. (1995) on winter rape.

Model  The CERES-Rape model we used in this work simulates the growth and development of winter oilseed rape as a function of routine climatic variables (solar radiation and air temperature) and of soil availability of N. In addition to its components related to crop growth, it comprises sub-models for soil water balance, nitrate movement and for the bio-transformations of soil carbon and N. CERES-Rape has been partly developed on the above described experiment in Champagne, and produced acceptable results against another data set in Denmark (Gabrielle et al., 1997).

In the original CERES root sub-model, the rooting depth MRD is a linear function of cumulative temperature in soil (base 0°C), as modulated by soil moisture content, and the distribution of the root length density RLD down the rooting zone is a mere function of MRD. The shape of the distribution is parameterised by a series of layer specific weighting factors, as proposed by Gerwitz and Page, 1974.

Field Results and Model Development

Fig. ?? provides an example of the root contacts distribution down a vertical face. There was a very strong influence of the type of subsoil encountered by the roots on their rate and density of penetration in the profile. The zones of compact chalk nearly prevented any exploration by the roots, whereas the vertical veins of altered chalk did not seem to oppose any mechanical impediment to root growth. Along the horizontal axis, each map covered roughly 9 rows, and
Figure 1: Typical map of root contacts (+) on a vertical face perpendicular to the 0.29-m rows for the N0 crop in early December, 1994. The stacked round symbols at the top indicate the position of the rows, which were used to assign a particular soil column to each plant. Overlaid is a pedological map of the face, emphasizing the lateral variability encountered in the subsoil where zones of compact, ochre chalk alternated with veins of coarse, grey cryo-altered chalk.
was subsequently divided into 9 sub-sections extending from one inter-row to the next. Within each of these sub-sections, any one root was assumed to have been emitted by the plants growing between the two inter-rows. This is of course a rather crude hypothesis, but it was necessary to derive plant-averaged quantities from the map. Due to subsoil variability, we had to separate the plants growing on compact chalk from those growing on the smooth veins of altered chalk. The latter category then gave potential figures, inherent to the plant itself, whereas the former one represented the effect of a mechanical stress on root growth.

There was no notable effect of N treatment on the dynamics of both rooting depth and density (Figure ??). In the subsequent modelling effort we then concentrated on the effect of soil temperature only. The first stage of model development regarded the dependence of MRD on soil temperature, as measured around the MRD. There was a good linear relationship \( R^2 = 0.98 \) between the ‘potential’ rooting depth data against thermal time (base 0\(^\circ\)C), with a slope of 0.08\(\text{cm} \cdot \text{C}^{-1} \) and a maximum of 140 cm reached around flowering. Data points from all N treatments fitted the same curve, which coefficient was abated by 40\% for the ‘stressed’ group (individual plants growing on compact chalk).

Next, Fig. ?? shows the increase of RLD for each 10-cm soil layer as a function of the distance from the layer to the rooting depth. There was a reasonable linear relationship with two different slopes for the topsoil and the subsoil layers. Because the points on Fig. ?? are averaged over the ‘potential’ and ‘stressed’ plant populations, there is a high scatter around these two straight lines. This was especially true for the layers that occupied an intermediate position between the rendzina topsoil (0-30 cm) and the mostly compact subsoil (60-120 cm), and the corresponding data (30-60 cm) were set aside in the regressions. In each soil layer that had been colonised, the variation of RLD was thus calculated as:

\[
\Delta \text{RLD} = RLD_{\text{max}} v_{\text{RLD}} \Delta Z_r
\]

where \( Z_r \) is the rooting depth (cm), \( RLD_{\text{max}} \) is the maximum RLD (set to 5 cm roots \( cm^{-3} \) soil, after Petersen et al. (1995), and \( v_{\text{RLD}} \) is the relative lateral extension rate (cm\(^{-1}\)). \( v_{\text{RLD}} \) is 1.33 in the topsoil and 0.25 underneath (Fig. ??).

The equations derived for MRD and RLD were implemented in the CERES-Rape model, and the model was run for all three experimental treatments. Fig. ?? shows the simulation of MRD and RLD for the N2 crop, against observed data. Although the equations had been calibrated on the same data set, the model tends to underestimate the RLD in the top layers of soil. This problem is probably linked to the high dispersion of the measured colonisation rates around the regression line in Fig. ??.

**Discussion and Conclusion**

Although the submodel proposed in this paper should be further tested against independent data sets, it is interesting to note that both rooting depth and rooting density could be mimicked based on the sole soil temperature. The absence of N effects on root growth, although the dry matter
Figure 2: Dynamics of the profiles of root contact frequency observed for the three N treatments.
Figure 3: Variations of root length density (RLD) in each 10-cm soil layer, for the three N treatments, as a function of the distance between soil layer and maximum rooting depth (MRD). The two solid lines are the linear regressions used for the topsoil (0-30 cm) and the subsoil (60-120 cm) layers.
and N contents of shoots and roots varied by a factor of three between the N treatments, has important consequences for the design of N nutrition experiments since it means that the root uptake capacity of a non-fertilised crop is representative of that of fertilised crops. This supports the assumption that the supply of mineral N from soil to fertilised crops may be estimated as the N uptake of a non-fertilised control crop.

From the modelling standpoint, while the form of the equations presented here is likely to hold for other crops or soil types (Jones et al., 1991), their parameterisation raises a far more critical issue. We may probably admit that there are potential parameters for MRD and RLD inherent to one crop type (e.g., rapeseed) but the question of possible mechanical constraints to root elongation from the soil needs to be specifically addressed. Unfortunately most field techniques that would provide the ‘stressed’ parameters are rather time-consuming. As an alternative, some authors have tried to devise mechanical stress indices based on soil texture or bulk density (e.g., Jones et al., 1991), which could roughly account for the variability observed here between the surface rendzina and the chalky subsoil. Whether this was a fortunate coincidence or not, given

Figure 4: Simulated (lines) and observed (bars and symbols) root length density (RLD), at five dates, and maximum rooting depth (bottom left graph) for the N2 treatment.

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that none of the data used to derive these factors pertained to rapeseed, it seems that efforts should be encouraged in the calibration of such indices. With our particular objectives of predicting crop N uptake, it may also be worthwhile to test the sensitivity of this variable to the root growth parameters. If the stress occurs sufficiently deep in the subsoil, for instance, it is likely that the use of potential parameters will yield similar results to those obtained with the actual parameters, thus dispensing with a field study.

References


