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Quantifying the effect of uncertainty in soil moisture characteristics on plant growth using a crop simulation model

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Abstract

For a given site, most readily available soil information is descriptive, qualitative and classifies soils according to origin, texture, colour and chemistry. Precise prediction of plant responses to lack of water or nutrients requires a quantitative description of moisture holding and release characteristics of soil that are often estimated from these descriptions rather than measured. In this paper we analyse the effect of uncertainty in soil description on the precision of simulated crop growth and development. This analysis suggests that accurate yield estimates depend on site-specific measurements. We demonstrate the significance of this imprecision by calculating the expected range of grain yields from a range of soils representing arable land in the UK using UK weathers and a realistic range of crop N-managements. A maximum grain yield range of 7 t/ha was found, representing a significant level of uncertainty. We conclude that since simulated yield can be so sensitive to the description of soil hydraulic properties, quantitative soil moisture characteristic measurements should be made in order to analyse plant growth in response to its environment.

Keywords: Water and nutrient availability; Crop simulation; Sirius model; Pedotransfer functions; Moisture retention and release

1. Introduction

Britain has a mild climate with generally plenty of rainy days and low evaporative demand. Such conditions have led to a perception among many researchers that crop production is seldom limited by water supply (French and Legg (1979) and Penman (1971)). It seems likely that water availability should be plentiful in such a climate; nevertheless, drought responses have been observed and measured for wheat grown in sandy soils in the UK (Foulkes et al., 2001, 2002). The areas where experiments supporting these two conclusions were carried out are geographically close, and have very much the same climate. Hence the soil and its moisture retention characteristics and capacities are the main cause of the differences. However, simply classifying a soil as clay or sand is unlikely to be sufficient to quantify or predict the likely reduction in yield associated with drought. Similarly, Canterbury in New Zealand, where most of that country's wheat is grown, is an alluvial plain with soils of varying thickness over gravel beds that are about 70% stones with soil between them. The major source of variation of root zone available water holding capacity in those soils is the depth of overlying soil which may vary from 15 cm to several metres. These variations lead to differences in optimum management (different optimum irrigation frequencies for example). If these optimum managements are not implemented, yield can vary substantially across soil types.

1.1. Crop model

Crop simulation models (the Sirius wheat simulation model is used as an example in this case: (Jamieson and Semenov, 2000; Jamieson et al., 1998b; Lawless et al., 2005) require several types of quantitative inputs in order to simulate the daily dynamics of crop growth and development. These inputs are:

(1) daily weather including minimum and maximum temperatures, rainfall and radiation;
(2) applied management; i.e., N and water added to the crop;

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(3) a physiological description of the cultivar under consideration;
(4) a description of the soil and its initial condition (since the soil is the buffer through which the plant experiences both weather and N-management).

Cultivar specific parameters are calibrated using independent experimental datasets and include parameters describing rate of phenological development, vernalization, sensitivity to photoperiod and rate of canopy development amongst others.

Daily weather data are typically used for input to crop simulation models since they are the most commonly measured data available. Daily data have been settled upon as a compromise between ease of measurement and capturing detailed weather response. It is not obvious that increasing weather measurement frequency will result in increased precision in crop modelling. These data are usually available either from an on-site meteorological station, or from one located within a few kilometres of the site under consideration.

It is a simple matter to record the amount and timing of N-application (and irrigation, where relevant).

All of the aforementioned inputs are compatible with those required by Sirius and other crop simulation models. However, often no quantitative soil description is available. Instead, soils are described via their type or class (examples: Alluvium/Biel and clay loam over Keuper marl 0–30 cm coarse angular blocky structure, brown clay loam 30–90 cm Pismatic coarse peds, red brown clay). Qualitative soil descriptions such as these are usually converted to crop-model-compatible quantitative parameters using a multi-step process. They are first converted to soil compositions (i.e. sand, clay fractions, etc.), using the USDA textural triangle for example. This induces a large degree of imprecision in the soil composition estimates. Then, these estimated compositions have to be converted to hydraulic properties using a pedotransfer function (Bouma, 1989 for example), which induces further imprecision. In a situation where crop simulation models are very sensitive to these input parameter values, and are expected to produce precise output predictions, this level of imprecision is unlikely to be acceptable. Some methodologies for analysing parameter sensitivity in complex models can be found in Hamby (1994).

The purpose of this work is to demonstrate how uncertainty in soil description affects model prediction of plant growth, and to assess whether this uncertainty induces significant imprecision in crop simulation predictions.

1.2. Investigating a wide range of conditions using a simulation model

The rigorous representation of scientific ideas in a systematic, mathematical framework (a model) allows us to carry out virtual experiments, keeping aspects of the plant's environment constant in ways that would not be possible experimentally. In this work, we use this technique (keeping weather, management and cultivar constant, while varying soil descriptions), to explore the effect of soil moisture retention on plant growth. We investigate the importance of interactions between rainfall, soil moisture and N-management and whether they are sufficiently well represented without a quantitative description of soil moisture characteristics. We do this by estimating the magnitude of their effect on simulated crop yield.

The magnitude of this effect has important implications for some experimental studies, since a component of the mechanisms connecting N-management to plant growth is ignored without quantitative soil descriptions. Under conditions where this effect is large, quantitative soil descriptions may be important when trying to unravel the effect of soil–weather-management interactions (e.g., in nitrogen-use efficiency or water-use efficiency studies).

This is not to say that such measurements should necessarily be at a single point. It is important to model mechanisms at a scale which is appropriate to the problem at hand, and within many problems there is spatial variation of soil properties. At a regional scale for example, the simulation of many different areas, each represented by separate soils might be appropriate. Even at the field scale, a field with noticeably different soil types (a field with an old riverbed running through it for example) could be split into separate sections (or management zones: Koch et al. (2004)) for simulation purposes if necessary. For experimental analysis, it should be possible to choose small plots with relatively low spatial variability. It is recognised that the spatial variability of soil characteristics can be significant, but efficiently dealing with this variability is a separate issue to the work presented here.

It is not currently clear how best to translate the qualitative information usually used to describe agricultural soils into the specific parameters that simulation models require for input, or whether, in a crop simulation context, any such translation can be considered useful. Any scheme for converting from this qualitative soil-type description will have limitations. Gijsman et al. (2003) consider the effect of such imprecision on a crop without N-limitation. They also described inconsistencies among pedotransfer functions. A qualitative description must, by definition, be coarser and less precise than a quantitative one, and so have associated with it an intrinsic range of feasible quantitative descriptions, and hence a range of feasible model outputs (grain yield, for example). This widened range of output results is indistinguishable from that which would be caused by model error, imprecision in cultivar-specific parameter values, etc. Qualitative descriptions are only inadequate when the magnitude of this blurring of output exceeds the required precision of the model. The predictive skill of a model is of great practical interest, but being unable to distinguish between model error and imprecise soil description precludes a rigorous assessment of model skill.

Detailed pressure-plate measurements of soil moisture retention curves are expensive and time-consuming. It is probably for these reasons that soil moisture release and retention characteristics are not commonly measured, and are either ignored, or crudely estimated from soil texture descriptions. To provide the simple soil description required as input to many simulation models, these expensive measurements might not be necessary. They can be partially