Modelling soil strength and its effects on winter wheat dry matter production

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Abstract

In order to apply irrigation water efficiently, it is of critical importance to understand how lack of water is stressing a crop. Soil strength can sometimes retard growth even when water is present in soil at relatively high matric potentials (e.g. >-80kPa). Accordingly we have modified a computer simulation model of soil water dynamics under a growing wheat crop to include the calculation of soil strength, as determined by the resistance to penetration. The combined model requires the moisture release curve (but can be derived from soil textural data), daily rainfall, temperature and potential evaporation and the agronomy of the crop and soil data. With this information, estimates of penetrometer pressure were simulated well compared with measured values in artificially strengthened (compacted) and weakened (irrigated) soils. Our aim was to develop a versatile model that could be used to infer effects of soil strength on a wide range of crop yield data from many different field trials.

Key Words

Computer simulation model, soil strength, drought, crop dry matter, matric potential, yield

Introduction

When crops or plants are exposed to drought they are subject to a number of abiotic stresses that sometimes act simultaneously to reduce growth. Certain stresses are inter-related: growth can be reduced by drought or an increase in soil strength (Masle and Passioura, 1987; Whitmore and Whalley, 2009) which is itself dependent on the soil water status (e.g. Greacen, 1960). The high correlation between soil strength and soil water potential has made it difficult to disentangle the effects of these separate stresses on plant growth except in laboratory experiments where it has been demonstrated that even under well-watered conditions, soil strength can reduce plant growth significantly (Masle and Passioura, 1987). In a series of recent articles Whalley *et al.* (2006; 2008) have demonstrated these effects in field-sown wheat.

Methods

Modelling

Whitmore and Whalley (2007) have shown how penetrometer pressure, Q, can be related to soil moisture status and bulk density:

$$\log_{10} Q = 0.35421\log_{10}\left|\psi_i S_i\right| + 0.9313\rho_i + 1.262 \qquad (1)$$

where ψ_i is the matric potential at depth i, S_i is the relative saturation and ρ_i is the bulk density. We have implemented a fully-implicit finite difference solution to Richard's equation (Richards, 1931) in one dimension for water flow in unsaturated soil in order to calculate ψ and S. In this way we can obtain a dynamic record of the change in soil strength during the growing season. Nitrogen supply from soil, and crop growth are as described by Whitmore (2007, 1995 respectively). Parameters for the water model can be derived from published pedotransfer functions (Wösten *et al*., 1999)

Sensitivity analysis

The sensitivity of the combined model to changes in texture, meteorological variables, bulk density and soil organic matter was tested by varying parameters in combination and examining the effect on penetrometer pressure in the spring under a growing crop.

Field data

Gregory *et al*. (2007) distinguished the effect of strong soil on winter wheat (Triticum aestivum cv. Clare) from drought by compacting the soil artificially in three contrasting soils at Silsoe in Bedfordshire, UK. Compaction was achieved by driving an 11 tonne tractor over plots 0, 1, or 8 times. The effect of compaction in unsaturated soil is to increase the bulk density and to reduce the number of large pores. Soil strength was recorded in both years on all plots with a Bush hand-held recording penetrometer (Findlay, Irvine Ltd, Penicuik, Midlothian, UK) fitted with a cone with a 30° angle and 130 mm^2 base area.

Meteorological data was taken from the nearby Woburn meteorological station (Lat: 52° 2′ N; Long: 0° 36′ W). Properties of the soils used to evaluate our model of soil strength are given in Table 1.

Table 1 Properties of the experimental fields.

Field name	Site	Soil	Org. C %	Sand %	Silt %	Clay %	ρ
Cashmore	Silsoe	Sandy loam	1.9	73	13	14	1.4
Cashmore	Silsoe	Sandy clay loam	2.5	65	15	20	1.3
Boot	Silsoe	Clay	2.6	12	22	66	0.90

Results

Model

Mean squared differences between measurement (Gregory *et al.*, 2007) and model were minimised on differences with log-transformed values of penetrometer resistance in soil; the transformation was used in order to stabilise the variances. Figure 1 plots the goodness of fit to data obtained during the 2004-2005 growing season under a crop of winter wheat. The root mean square error of prediction of Q was 485 kPa for measurements made during the growing season between November and June.

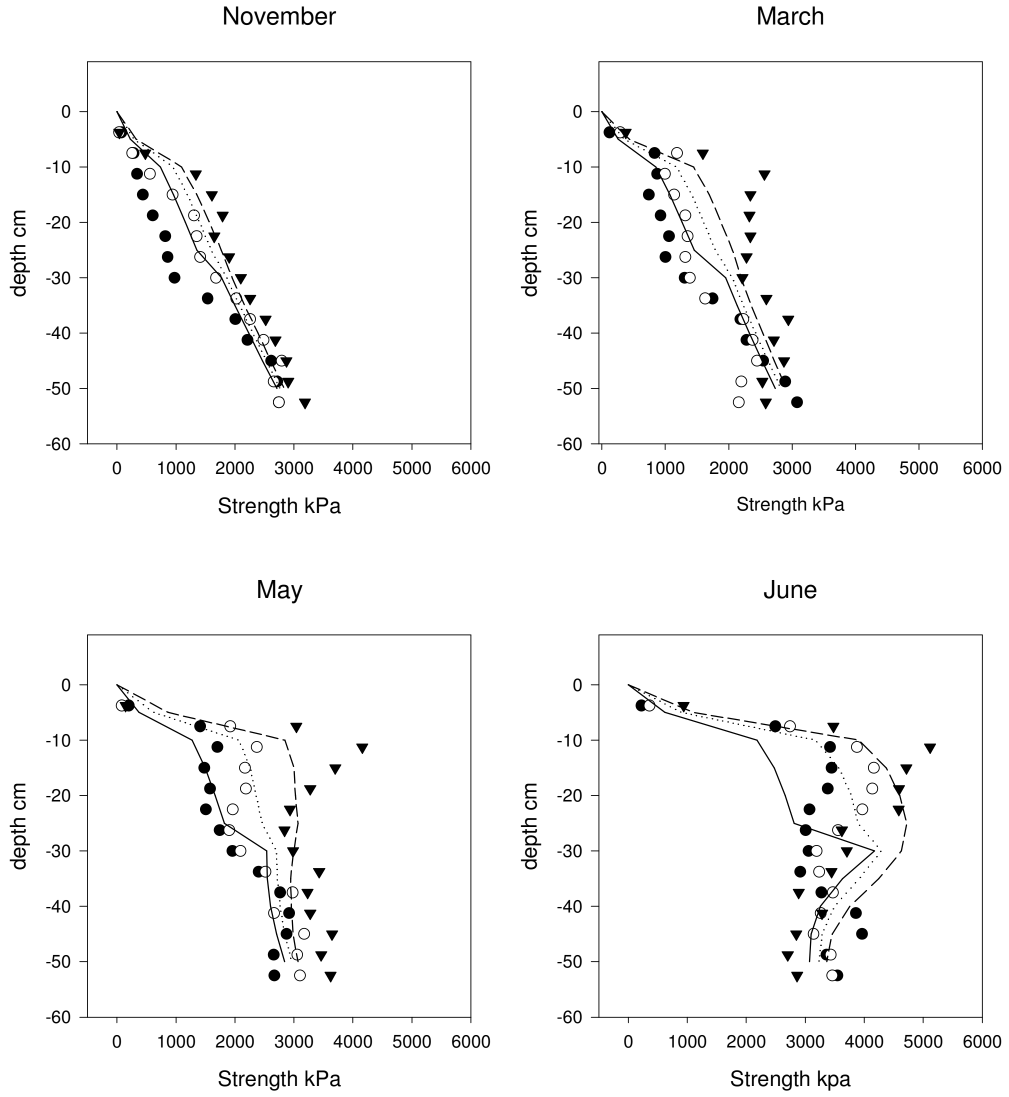

Figure 1. Fit of the model to measurements of penetrometer pressure under a field of growing wheat during 2004-5 on a sandy clay loam soil at Woburn. Symbols: measurements; lines: model. Closed circles, no compaction, open circles, one pass from a 10 tonne tractor; triangles, 8 passes. Solid, dotted and dashed lines, 0,1 &8 passes respectively.

With these data and those from other experiments on winter wheat (Whalley *et al*., 2006; 2008), we were able to infer the effect of soil drying prior to anthesis on final yields of crop dry matter.

Sensitivity analysis

Modelled Q is somewhat sensitive to changes with rainfall but not to temperature or evaporation (Figure 2). Note that these are for typical values in southern England. In parts of the world where evaporation or temperature have greater ranges, Q might vary more. In general, rainfall can probably be measured with sufficient accuracy for this model, but the issue in practice will be whether appropriate, i.e. on-site rainfall data is available. Data from a distant meteorological station might differ from the actual local conditions. Q changed by about 15% with a change in clay from 10 to 50% (Fig 2). Q was not sensitive to changes in soil organic matter (SOM, data not shown) nor to changes in silt content in isolation (data not shown). Clay and SOM can almost certainly be obtained with sufficient accuracy for use in this model. Both quantities vary extensively over short distances in space, however (eg Watts *et al*., 2006). Penetrometer resistance is quite sensitive to changes in bulk density (Fig 2). A change in bulk density of 0.15 units, from say 1.3 to 1.45 results in a change in Q of almost 18% assuming all other factors such as clay content held constant. The changes in Q are more marked at the denser end of the range tested and the 70% change in ρ shown in Figure 2 can result in a 100% change in Q.

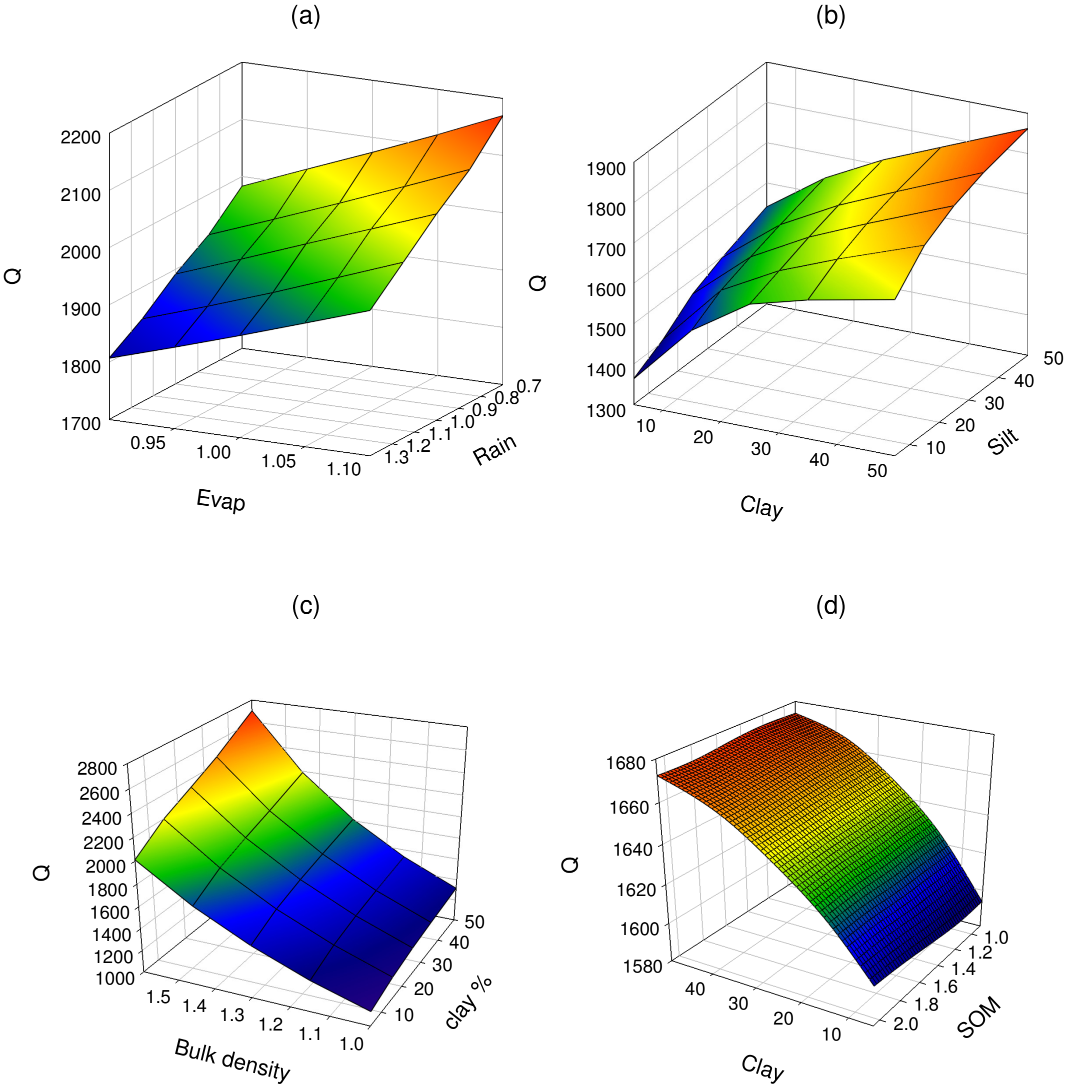

Figure 2. Sensitivity of Q in the model to changes in rain, evaporation (a), clay and silt (b), bulk density and clay content of soil (c), clay and SOM content (d).

Conclusions

Penetrometer pressure, Q, was predicted well by our model, and so we may regard the model as a useful means to estimate soil strength under crops grown in standard agricultural practise during the critical period of interest when the soil is dry enough to impede root growth but not so dry that crop is permanently wilted.

The data needed to run the model can be obtained with sufficient accuracy for us to have confidence in the values of Q predicted. In use, most effort should be put into obtaining good estimates of rainfall and the bulk density of a soil.

The next steps of this work are to compare the effects of both matric potential and soil strength in the field on crop yield and to try to assess the most effectiveness manner of irrigation.

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