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Predicting soil moisture conditions for arable free draining soils in Ireland under spring cereal crop production

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Temporal prediction of soil moisture and evapotranspiration has a crucial role in agricultural and environmental management. A lack of Irish models for predicting evapotranspiration and soil moisture conditions for arable soils still represents a knowledge gap in this particular area of Irish agro-climatic modelling. The soil moisture deficit (SMD) crop model presented in this paper is based on the SMD hybrid model for Irish grassland (Schulte *et al*., 2005). Crop and site specific components (free-draining soil) have been integrated in the new model, which was calibrated and tested using soil tension measurements from two experimental sites located on a well-drained soil under spring barley cultivation in south-eastern Ireland. Calibration of the model gave an R^2 of 0.71 for the relationship between predicted SMD and measured soil tension, while model testing yielded R^2 values of 0.67 and 0.65 (two sites). The crop model presented here is designed to predict soil moisture conditions and effective drainage (i.e., leaching events). The model provided reasonable predictions of soil moisture conditions and effective drainage within its boundaries, i.e., free-draining land used for spring cereal production under Irish conditions. In general, the model is simple and practical due to the small number of required input parameters, and due to model outputs that have good practical applicability, such as for computing the cumulative amount of water-soluble nutrients leached from arable land under spring cereals in free-draining soils.

Keywords: agro-meteorological modelling; arable land; nitrate leaching; soil moisture deficit

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Introduction

Since the Irish climate is classified as oceanic to near oceanic with temperate summers and mild winters (Keane, Barry and Stafford, 1992), studies of nitrate leaching from tillage land are particularly important due to potential for mineralization of soil organic matter during the winter (Hooker *et al*., 2008). Tillage systems can also have increased mineralization of soil organic matter and increased release of nitrogen due to ploughing (Addiscott, 1996). It is also known that land under tillage farming can have a higher risk of nitrate loss than grassland (Webster and Dowdell, 1986; Ryan and Fanning, 1996; Thomsen and Christensen, 1998). For these reasons, a simple model for predicting soil moisture conditions for tillage systems in Ireland should be very useful for various agronomic and environmental studies that are performed on Irish arable land, and this represents one of the main objectives of this study.

Temporal prediction of soil moisture and evapotranspiration has a crucial role in agricultural and environmental management. Estimates of soil moisture conditions are frequently required in agriculture for issues such as the estimation of water use by crops (Abdelhadi *et al*., 2000), drought monitoring (Narasimhan and Srinivasan, 2005) or irrigation scheduling, and crop water-use studies (Bailey and Spackman, 1996). Therefore, this information has an important role in crop production management. These examples show that temporal variations in soil moisture represent a significant factor determining crop growth.

Various examples of models used for predicting soil moisture conditions can be found in the literature. One of the well known models is MORECS (Hough and Jones, 1997) developed in the UK for estimating evapotranspiration, soil moisture conditions and effective rainfall. Among other things, the MORECS model can be used for calculating effective rainfall in agricultural studies (e.g., see Lord and Shepherd (1993)). Another example of a well known and frequently used model for crop management is the CROPWAT model, originally developed by Smith (1992) to predict crop requirements for water.

In addition to their role in crop management, predictions of soil moisture conditions and related evapotranspiration are very important for environmental management. For example, the prediction of evapotranspiration is frequently used in hydrological models for river catchments, such as SWAT, or in hydrological N-load models, such as SWAT-N (e.g., Jha *et al.*, 2006; Pohlert *et al.*, 2007). In addition, hydrogeological studies often use water balance modelling that involves prediction of effective drainage (or effective rainfall). Thus, Misstear, Brown and Johnston (2009) used soil moisture budgeting for computing effective rainfall, which can be used for the purpose of estimating groundwater recharge by multiplying it with a recharge coefficient.

Models for soil moisture prediction also have a crucial role in investigating leaching losses of water-soluble pollutants to soil and groundwater, often carried out in studies of diffuse agricultural pollution. If soil moisture exceeds field capacity, this can increase the risk of leaching of water-soluble nutrients (such as nitrate). Prediction of temporal variations in soil moisture conditions and the amount of effective rainfall/drainage are therefore necessary for computing cumulative nitrate leaching. Studies of nitrate leaching losses from agricultural systems often include drainage period predictions and calculations of nitrate leaching based on the predicted water flux/drainage. Examples include Shepherd (1996), who used a modified Penman-Monteith (Allen *et al*., 1998) equation, and Johnson, Shepherd and Smith (1997), Beckwith *et al.* (1998) and Smith *et al*. (2002), who used the Irriguide computer program, which is based on MORECS (Thompson, Barrie and Ayles, 1981). Further, Johnsson *et al*. (2002) presented the SOILNDB tool model for agricultural management of leaching that is based on the SOIL and SOILN models (Jansson and Halldin, 1979; Johnsson *et al.,* 1987) with water balance calculation based on the Penman-Monteith equation.

Irish models that involve soil moisture prediction and evapotranspiration estimation are mainly used for water budgeting in connection with studies on grassland management and grass productivity; e.g., Lewis and McGechan (1999), Moehrlen, Kiely and Pahlow (1999), Clifton-Brown *et al*. (2000); Mills (2000); Lewis, McGechan and McTaggart (2003) and Charlton *et al.* (2006). These models were developed mainly for the modelling of overall water-budgets at large scales, or for modelling hydrogeological cycle components. An Irish model that predicts soil moisture dynamics for grassland at the field scale is the soil moisture deficit (SMD) hybrid model of Schulte *et al.* (2005).

The lack of Irish agro-meteorological models for tillage land represents a knowledge gap in this particular area of modelling. An attempt at filling some parts of this knowledge gap has been made in this study by developing a soil moisture deficit model for predicting soil moisture conditions on a free-draining arable soil under spring cereal cultivation in Ireland. This SMD crop model is based on the SMD hybrid model (Schulte *et al.,* 2005), and can be classified as a dynamic deterministic model. The original hybrid model was developed in line with FAO (Food and Agriculture Organisation) guidelines for computing evapotranspiration, and was calibrated and tested for grasslands on contrasting soils in Ireland. The objective of this study was to develop a simple SMD model for crops that is practical and enables prediction of SMD and effective drainage using minimal meteorological data.

Model description

Background

The soil moisture deficit is often used for quantification of soil moisture conditions and is expressed as the rainfall required for restoration of soil moisture to field capacity (Price, 2002). The Penman-Monteith equation (Monteith, 1973) allows the estimation of the potential (or reference-crop) evapotranspiration, from a standardised, properly watered reference-grass surface, that occurs when the water supply is not restricted (Allen *et al*., 1998; Davie, 2008). The evapotranspiration that occurs is the actual evapotranspiration (Allen *et al*., 1998; Davie, 2008). If the water supply is restricted, and the soil moisture deficit increases, the actual evapotranspiration will be reduced and actual evapotranspiration will be lower than potential evapotranspiration (Keane *et al*., 1992). Therefore, the ratio between actual evapotranspiration and potential evapotranspiration is closely correlated with the soil moisture deficit.

Most hydrological models are designed with the purpose of solving the water balance equation for a given time period (Davie, 2008). Davie (2008) identified the Penman-Monteith method as one of the best evapotranspiration methods available today, while the FAO strongly recommends this method for estimating the potential evapotranspiration (Et_o). In addition, the FAO also lists a number of

Et_o ranges typical for some agro-climatic regions (Allen *et al*., 1998). It should be borne in mind that the application of the water balance equation in models still involves imprecision due to the spatial and temporal scale of the hydrological processes involved; and this scale may not be the same as the scale of estimated measurements (Davie, 2008).

Because actual evapotranspiration is a function of soil moisture deficit and potential evapotranspiration, this relationship, together with field soil tension measurements, can be used to develop and calibrate a simple SMD model, such as the SMD hybrid grassland model. This specific grassland model, which uses the Penman-Monteith method to estimate Et_o, was developed for predicting actual evapotranspiration using the predicted temporal soil moisture deficit variation in the rooting zone of Irish grasslands on well-drained and poorly-drained soils (Schulte *et al*., 2005). Its development was based on a combination of two approaches (hence a "hybrid" model) for calculation of soil moisture deficit. The two approaches were the Teagasc model (Brereton, Danielov and Scott, 1996), which predicts SMD for well-drained soils, and the Met Éireann model (Keane, 2001), which predicts SMD for poorly-drained soils. The main advantage of this grassland model is its practicability due to minimum requirements for data input. The SMD crop model presented in this paper, which is based on the existing SMD hybrid grassland model, involved further computing of crop evapotranspiration, including the estimation of parameters for various crop growth stages, as well as model calibration and model testing for site specific conditions.

Model computing

The SMD crop model uses site characteristics and meteorological data for the simulation of soil moisture conditions and evapotranspiration. The inputs and expected outputs are summarized in Table 1. The soil moisture deficit, radiation and drainage are calculated as described in Schulte *et al*. (2005), which is a water-mass balance daily time-step procedure based on Aslyng (1965) and using the Penman-Monteith equation (Allen *et al*., 1998). Consequently, some of the common components of the crop model presented here have been taken directly from the SMD hybrid model for grassland; these involve calculation of soil moisture deficit, calculation of the potential and actual evapotranspiration during the over-winter natural-regeneration period, and radiation. On the other hand, the crop- and soil-specific components were developed specifically for the SMD crop model for spring cereal production systems on free-draining soil. These components were:

- calculation of crop-specific coefficients,
- construction of crop coefficient curve,
- computing the reference evapotranspiration for spring cereal crops,
- the drainage component of the crop and soil specific parameters, which involved model calibration using the soil tension measurements from one field experiment and model testing using the measurements from an independent field experiment.

Table 1. Input parameters and outputs for the SMD crop model

Inputs	Outputs
Latitude	Soil moisture deficit
Altitude	Effective drainage
Daily temperatures (maximum & minimum)	
Wind speed	
Rainfall	
Radiation (or sunshine hours)	

Soil-water balance components

Soil moisture deficit is calculated as (Allen *et al*., 1998; Schulte *et al*., 2005):

$$\mathrm{SMD_t} = \mathrm{SMD_{t-1}} - \mathrm{Rain_t} + Et_a + \mathrm{Drain_t} \quad [1]$$

where $\mathrm{SMD_t}$ represents the soil moisture deficit (mm) on day t, $\mathrm{SMD_{t-1}}$ is soil moisture deficit on day t-1, $\mathrm{Rain_t}$ is an input variable of daily precipitation (mm/day), Et_a is actual evapotranspiration (mm/day) and $\mathrm{Drain_t}$ is water drainage rate (mm/day) by percolation and/or overland flow. Topsoil characteristics control the drainage rate and thus these are site-specific parameters (calibrated). On the other hand, the equation for the effective drainage is the same for the SMD hybrid model, and is calculated from Eq. 1 as $\mathrm{SMD_t} - \mathrm{SMD_{t-1}} + \mathrm{Rain_t} - Et_a$.

Due to difficulty in quantifying the precise relationship between actual drainage rate and SMD, Schulte *et al*. (2005) specified $\mathrm{Drain_t}$, when SMD $\leq$ 0, as:

$$\mathrm{Drain_{max}}\,(\mathrm{SMD_{t-1}}/\mathrm{SMD_{min}}),$$

$$\text{if } \mathrm{Drain_{max}} \leq -\mathrm{SMD_{min}}$$

and

$$-\mathrm{SMD_{t-1},} \quad \text{if } \mathrm{Drain_{max}} > -\mathrm{SMD_{min}}\,. \quad [2]$$

where $\mathrm{Drain_{max}}$ is the maximum drainage rate and $\mathrm{SMD_{min}}$ is the minimum value for soil moisture deficit (i.e., point of saturation that can have negative SMD value). The original hybrid model differentiated between poorly-, moderately- and well-drained soils by calibrating specific parameters for each drainage class, i.e., $\mathrm{Drain_{max}}$, $\mathrm{SMD_{min}}$ and $\mathrm{SMD_c}$ (the critical soil moisture deficit above which evaopotranspiration rate is reduced). Because the current model has been developed only for well-drained soil, $\mathrm{SMD_{min}}$ has been assumed to be zero because, by definition, these soils cannot reach saturation point (Schulte *et al*., 2005). For well-drained soils, the parameter $\mathrm{Drain_{max}}$ is redundant (Schulte *et al*., 2005). The crop- and site-specific parameters $\mathrm{SMD_c}$ and $\mathrm{SMD_{max}}$ (maximum soil moisture deficit) were calibrated using soil tension measurements from one of the experimental sites.

Evapotranspiration components

Actual evapotranspiration during over-winter natural-regeneration growth is calculated the same way as in the SMD hybrid model. When soil moisture conditions are not limiting plant growth, SMD is between field capacity (SMD = 0) and $\mathrm{SMD_c}$, then $Et_o = Et_a$. When $\mathrm{SMD_t} > \mathrm{SMD_c}$ the actual evapotranspiration will be reduced and will be less than Et_o, since the plants will be closing their leaf stomata to reduce transpiration due to lack of water (Aslyng, 1965; Allen *et al*., 1998) and under this condition:

$$Et_a = ET_o\,[\mathrm{SMD_{max}} - \mathrm{SMD_{t-1}}]/[\mathrm{SMD_{max}} - \mathrm{SMD_c}]\,. \quad [3]$$

The parameters used in the Penman-Monteith equation were determined from the meteorological data collected at Oak Park weather station (daily precipitation (mm/day), global radiation (MJ $\mathrm{m^{-2}\,day^{-1}}$), maximum and minimum temperatures (°C), wind speed (m/s) at 10 m above ground level, negligible ground-heat flux, albedo of grass crop 0.23, site latitude (radians) and altitude (m)). Required radiation input data were calculated from sunshine hours for the days with no available data on global radiation (Allen *et al*., 1998).

Reference evapotranspiration for spring cereal crops and construction of crop coefficient curve

The ET_o is the evapotranspiration from the standardised reference surface, while the reference-crop evapotranspiration (Eto_{crop}) is the evapotranspiration under non-standard conditions (i.e., other crop growing surfaces). Therefore the evapotranspiration needs correction in the form of crop growth coefficients (K_c; Allen *et al*., 1998) as:

$$Eto_{crop} = K_c \, Et_o \,. \qquad [4]$$

The Eto_{crop} values for spring cereal crops (spring barley and spring wheat) are determined according to FAO guidelines for computing water requirements for crops (Allen *et al*., 1998) through the following steps:

- identification of crop growth stages and determination of the corresponding K_c coefficients,
- adjustment of K_c for frequency of wetting-climatic conditions,
- construction of crop coefficient curve (K_c values for any period during the growth),
- calculation of Eto_{crop} using Eq. 4.

The growing period of the crop was divided into four growth stages, according to FAO guidelines (Allen *et al*., 1998). The initial stage (L_{ini}) is from the date of seed application to about 10% ground cover; the crop development stage (L_{dev}) lasts from end of L_{ini} until the effective plant cover has reached 100%; next is the mid-season stage (L_{mid}), which is generally the longest stage and lasts until the beginning of plant maturity; this is followed by the late season stage (L_{late}) that ends with full plant senescence or when the crop dries out naturally (Allen *et al*., 1998). The chosen growth stages for cereals sown during March/April are: 20 days for L_{ini}, 25 days for L_{dev}, 60 days for L_{mid}, and 30 days for L_{late}. Plant growth phases were not empirically determined; the default values given by Allen *et al*. (1998) were used.

The "graphical determination of Kc_{ini}", as outlined in the FAO guidelines, was used to estimate the crop coefficient for the initial stage in this paper (Kc_{ini}), based on the relationship between average Kc_{ini} and Et_o (Allen *et al*., 1998). The crop coefficient for mid-season (Kc_{mid}) was determined by two approaches:

- calculated following Allen *et al.* (1998), and
- using the value listed by Allen *et al.* (1998).

The crop coefficient for the final stage (Kc_{end}) was determined according to Allen *et al*. (1998), while the daily values for the coefficient during the development stage and the late stage were obtained by linear interpolation (Allen *et al*., 1998). It was assumed that after the late stage, Kc_{end} returns to 1, corresponding to the coefficient of actual evapotranspiration (Et_a) for a grass cover.

Actual evapotranspiration during the crop growth stages

Eto_{crop} was used in the SMD crop model for the calculation of Et_a during the crop growth stages. Actual evapotranspiration was calculated according to Eq. 3, by replacing the Et_o with the Eto_{crop}.

Experimental methods

Two experimental sites were used in this study: the Sawmills Field and Road Field. Both sites represent well-drained tillage land under cereal production (spring barley) at Oak Park Research Centre, Co. Carlow, Ireland (52°86′N, 6°92′W, altitude 54 m), and are relatively shallow with sandy and gravelly top soil, with a low water holding capacity, that is very prone to leaching. The two sites are about 300 m apart and both are very close to the River Barrow (500 to 800 m away).

Soil tension was measured at both sites using tensiometers (SDEC, Reignac sur Indre, France), and was recorded at fortnightly intervals using a digital tensimeter with attached hypodermic needle displaying the soil tension values. Tensiometers were installed at depths of 0.3 m and 0.6 m (due to very low soil water holding capacity of both experimental sites, causing very fast vertical movement of water through the soil). The tension measurements (n=2 per depth) from Sawmills Field were used for model calibration and were collected between January 2007 and January 2008; the Road Field measurements (n=4 per depth) which were used for model evaluation and were collected between December 2004 and September 2007. Additional evaluation of the model was done using measurements (between January 2008 and March 2009) from Sawmills Field.

Model calibration and testing

The model simulation using meteorological data was done for the period from 5 January 2002 to 16 September 2008. A wet period was deliberately chosen for the start of the simulation, when the initial value of SMD was assumed to be equal to SMD_{min} [as in Schulte *et al*. (2005)].

The crop coefficients (K_c) for each stage of crop growth were used for calculating the reference and actual evapotranspiration for spring cereals. The SMD crop model allows the standard reference-evapotranspiration (Et_o) to change to crop reference evapotranspiration ($Et_{o_{crop}}$) for the growth period of spring-cereal crops. This was done first by inputting meteorological data from January 2002 onwards in order to compute the reference evapotranspiration, and then by applying the appropriate K_c for each growth stage to generate the $Et_{o_{crop}}$ during each stage. Et_o was retained for the period of over-winter natural-regeneration growth between harvest and sowing. The above procedure resulted in the construction of the temporal crop coefficient curve. The effective drainage and soil moisture deficit were then computed.

The model was calibrated by correlating the predicted SMD with the observed soil moisture tension. Schulte *et al*. (2005) found that, for Irish conditions, the relationship between SMD and measured soil tension was close to linear for a wide range of potential parameter values. Therefore, a similar approach was adopted in the present study as this resulted in the same model performance, while requiring fewer input parameters. Simple correlation coefficients were computed between the predicted SMD values and measured soil moisture tension at 0.3 m depth and for the average soil tension at two depths (0.3 m and 0.6 m) for the year 2007. Calibration of the model was performed by choosing values for SMD_{c} and SMD_{max} that maximised the correlation coefficient, using Microsoft Excel 2003 Solver (under constraints $\text{SMD}_{\text{c}} > 0$ and $\text{SMD}_{\text{max}} > 0$). Testing of the model was performed by comparing predicted SMD from the calibrated model against average soil moisture tensions measured at 0.3 m and 0.6 m depths from the Road Field (for December 2004 to September 2007) and from Sawmills Field (for the year 2008). Three measurements with an uncertain level of precision due to poor equipment performance on the day of measurement (slightly bent tensimeter needle), were identified as outliers and were excluded from model testing. However, these three outliers were still acceptable for evaluation of leaching events, which does not need a high level of precision.

Model verification

The seasonal variability and the range of predicted total monthly values of $Et_{o_{crop}}$ from this model were evaluated against potential evapotranspiration values (predicted and/or measured; Met Éireann, 2006–2008) from Irish weather stations at Kilkenny, in Co. Kilkenny, and Johnstown Castle, in Co. Wexford (data not shown).

Model performance was also verified by comparing predicted and observed effective drainage, as one of the most important model outputs. The vertical transport of water from surface to greater depth (leaching) can occur only if the effective drainage is above zero. Tensiometers installed at depths of 0.3 m and 0.6 m were used to interpret the vertical water flux within the soil and the periods between measurement dates (observations) were classified as either leaching or non-leaching periods based on the actual soil tension measurements. Tensiometer readings at different depths can be used to predict leaching events due to the downward direction of water flux within the soil, resulting in an increase in soil tension. Leaching occurs when the measured soil tension at shallower depth is less than that at a greater depth. Based on the predicted daily effective drainage values, the same observation periods (as above) were classified as leaching or non-leaching, depending on the following conditions:

- leaching can occur only if the effective drainage is > 0,
- observation period was categorised as a leaching period if effective drainage was >0 for more than 50% of the total number of days within the period,
- observation period was categorised as a leaching period if the mean daily effective drainage for the period exceeded 0.5 mm (regardless of the proportion of days when the effective drainage was >0).

Results

Reference evapotranspiration for spring cereal crops and crop coefficient curve

The $Et_{o_{crop}}$ values for spring cereal crops determined using Eq. 4, with assigned K_c coefficients for initial (0.86), mid (1.15) and final stages (0.25) and the values for the developing and late stages calculated by linear interpolation (Allen *et al*., 1998), as explained earlier, with sowing on day 74 (day 1 = 1 January). Because the calculated crop coefficient for mid-season resulted in an underestimation of Kc_{mid} (0.92), the value of 1.15 (listed in Allen *et al*. (1998)) was chosen as a better estimate of Kc_{mid}. Determination of the K_c coefficients provided a crop coefficient curve typical for spring cereal crops under the soil specific conditions (Figure 1 is an example of the crop coefficient curve).

Model calibration and testing

The calibration of site-specific parameters using soil tension measurements from the Sawmills Field resulted in a value of 50 mm for $\mathrm{SMD}_{\mathrm{max}}$, while $\mathrm{SMD}_{\mathrm{c}}$ was zero. The best result for the correlation between SMD and soil moisture tension (R^2 0.71) was obtained using the average of values measured at 0.3 m and 0.6 m depths (Figure 2).

Model testing yielded an R^2 of 0.67 using data from Road Field, and 0.65 for data from Sawmills Field (Figures 3 and 4). The intercept of approximately −68 to −71 hPa on the soil tension axis (Figure 5a,b) shows higher actual soil tension at predicted field capacity.

Model verification

Simulated potential evapotranspiration: The predicted potential evapotranspiration obtained from the model ($Et_{o_{crop}}$ >20 and <100 mm) showed seasonal variability with slightly higher values during

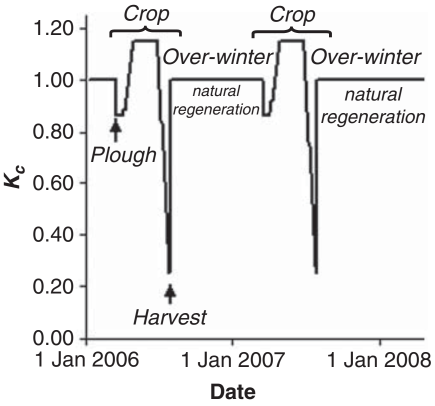

Figure 1. An example of constructed crop coefficient (K_c) curve for spring cereal crops for 3-year period commencing from 1 January 2006 (derived from assigning K_c values for each growth stage, with labeled events of ploughing, harvest, and the periods of growth of over-winter natural regeneration and spring cereal crop).

the winter period and an evident drop during June/July (before the harvest; data not shown). The predicted $Et_{o_{crop}}$ followed the general pattern of other selected Met Éireann predicted and/or measured Et_o values in Ireland using different methods (data from Kilkenny and Wexford; results not shown) (Met Éireann, 2006–2008). Because different methods were used for predicting or measuring Et_o at different sites, the evaluation of $Et_{o_{crop}}$ should be interpreted with caution.

Simulation of effective drainage: Tensiometer measurements at depths of 0.3 m and 0.6 m, and the resulting observed leaching periods for the Sawmills Field, are shown in Figure 6 along with the leaching events predicted by the SMD crop model for the period of time between 11 January 2007 and 27 July 2008 (560 days). The observed number of leaching days (309) was very close to the predicted number of leaching days (295). The measured and predicted leaching and non-leaching events also show reasonably good accuracy (70%; i.e., the sum of correctly predicted leaching and non-leaching events relative to total number of days), sensitivity (71%; i.e., correctly predicted leaching events relative to total predicted number) and specificity (69%; i.e., correctly predicted non-leaching days relative to the predicted number) (Table 2; Figure 6).

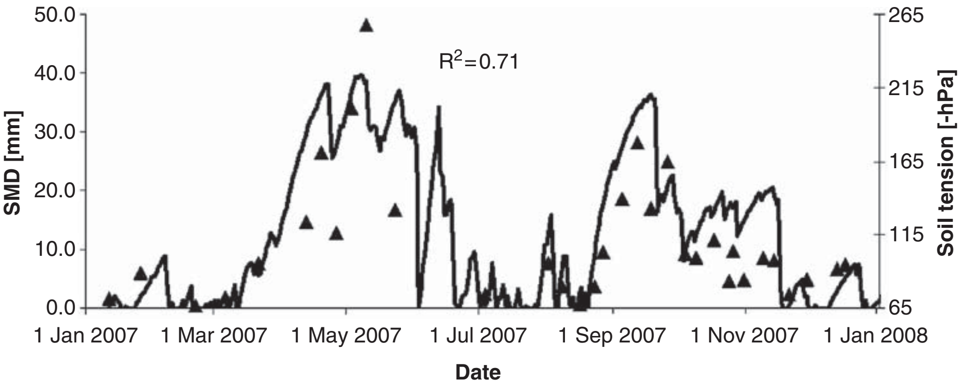

Figure 2. Model calibration: predicted soil moisture deficit (SMD) and measured soil tension (average of measured values at 0.3 and 0.6 m depth) for Sawmills Field. — Predicted SMD; ▲ Average soil tension at 0.3 and 0.6 m depth.

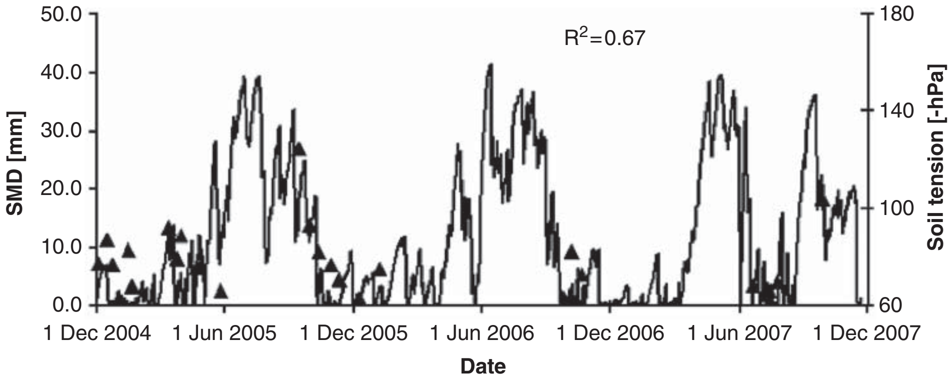

Figure 3. Model testing: predicted soil moisture deficit (SMD) and measured soil tension (average of measured values at 0.3 and 0.6 m depth) for Road Field. — Predicted SMD; ▲ Average soil tension at 0.3m & 0.6m depth.

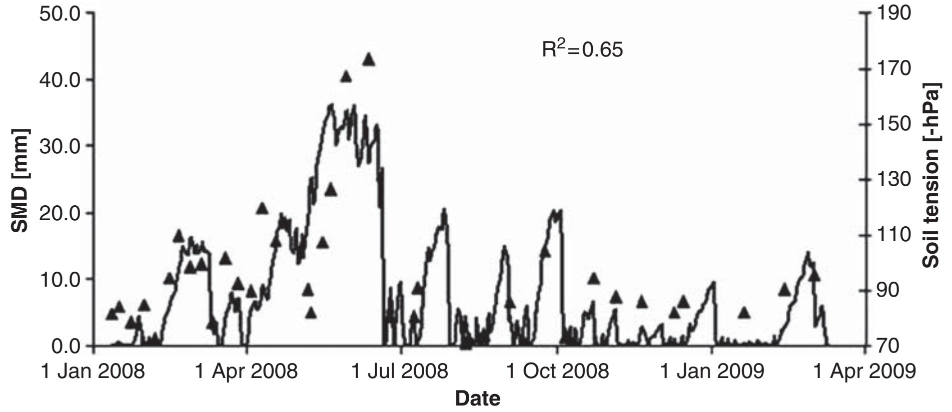

Figure 4. Model testing: predicted soil moisture deficit SMD vs. measured soil tension (average of measured values at 0.3 and 0.6 m depth) for Sawmills Field between January 2008 and March 2009. — Predicted SMD; ▲ Average soil tension at 0.3m & 0.6m depth.

Discussion

Model applicability and limitations

The SMD crop model presented in this paper was developed for predicting temporal changes of soil moisture conditions on a high-risk site with free-draining soil under spring cereal production in Ireland (i.e., crop sown in March and harvested in August) followed by over-winter natural-regeneration growth (weeds spontaneously growing during the winter drainage period).

The SMD crop model is a simple model that predicts effective rainfall and soil moisture conditions for spring cereal production systems on a free draining soil in Ireland. The model is practicable due to the small number of basic meteorological input parameters required, and model outputs that have high practical applicability, such as for computing the cumulative amount of water-soluble nutrients leached, or for calculating a general water balance.

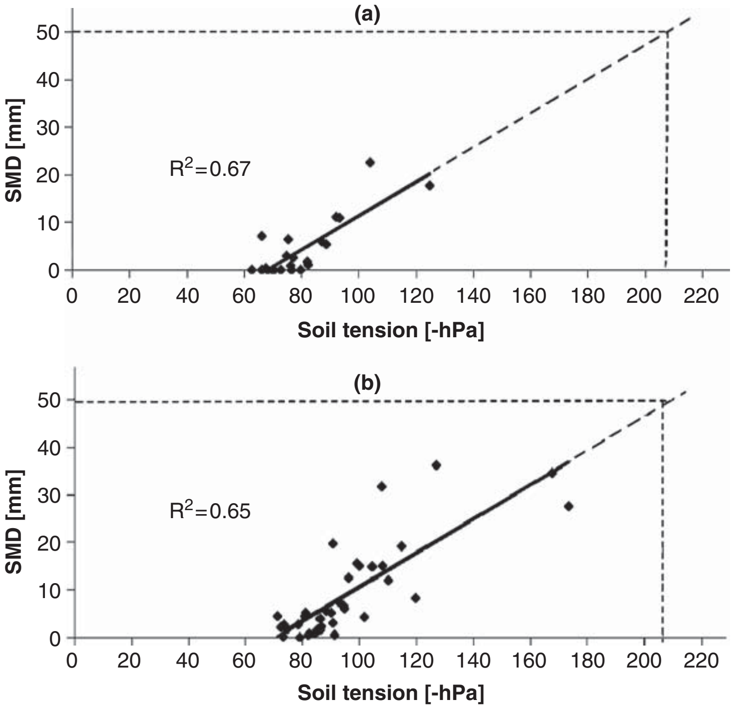

Figure 5. Predicted soil moisture deficit (SMD) vs. measured soil tension for: (a) Road Field (December 2004 to September 2007), and (b) Sawmills Field (January 2008 to March 2009).

However, as mentioned previously, application of the water balance equation in models can involve imprecision due to possibly different spatial and temporal scales of the hydrological processes compared with the scale of estimated measurements (Davie, 2008). Therefore some bias can occur due to the different temporal scales. The model was calibrated for the period from January 2007 to January 2008 using soil tension measurements on an approximately fortnightly basis, while it is used for predicting soil moisture deficit on a daily basis. Other possible bias in this model could potentially occur due to specific conditions at the two experimental sites used for model development. Both experimental sites have very low water-holding capacity and this factor could cause site-specific model limitations.

Model calibration and testing

In general, the ideal soil for crop growth should have sufficiently high water holding capacity, due to small pores to hold enough water for plant growth, but at the same time it should allow free drainage (from the larger pores) to facilitate soil aeration for respiration of soil organisms and plant roots (Price, 2002). This is often not the case, such as for the soils in the Sawmills and Road fields. In case of a well-draining coarse soil, such as sands and gravels, the water will drain easily after rainfall (Price, 2002). It is possible that a lack of small pores to hold the water at 0.3 m depth for a sufficiently

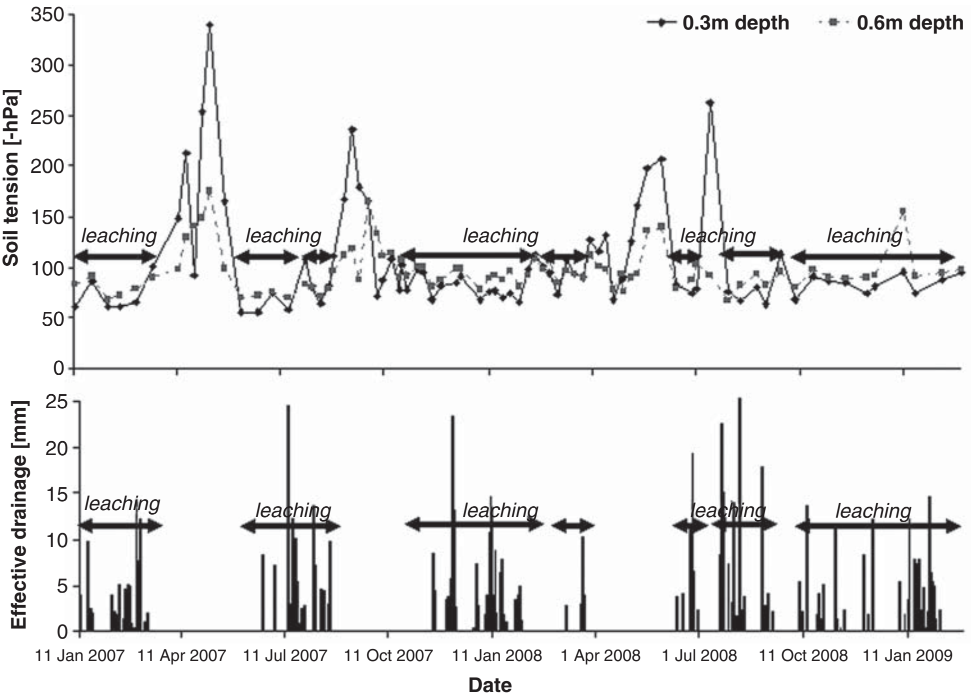

Figure 6. Predicted periods of leaching from modelled effective drainage and from soil tension field measurements.

long time resulted in very fast draining of the soil water to greater depth (0.6 m). The recommended depth for installing tensiometers depends on soil type and on plant rooting zone depth. The model calibration results in this study suggest that the appropriate soil depth for measuring soil tension is approximately 0.45 m, which is mainly a function of free-draining soil characteristics, and less a function of crop rooting depth in this particular case. However, it should be kept in mind that the rooting depth depends on crop type and other environmental conditions (e.g., temperature, climate), and therefore this needs to be taken into account if studies are performed on different crop or soil types.

The lower SMD_{max} in the crop model (50 mm) compared with a value of 110 for the SMD hybrid model for grassland (Schulte *et al*., 2005) indicates that SMD_{max} is most probably a function of the low water-holding capacity of the soil at the selected site. The correspondingly lower soil tension (Figure 5a and b) also indicates a possible faster occurrence of the plant wilting point on this very coarse soil, due to its poor capability to hold water.

The simple correlation coefficients should be interpreted with caution, since

Table 2. Number of observed and predicted leaching and non-leaching days during a period of 560 days (11 January 2007 to 27 July 2008)

Observed event	Predicted event		Totals
	Leaching	Non-leaching	
Leaching	218	91	309
Non-leaching	77	174	251
Totals	295	265	560

the data (Figure 5a and b) fall into two broad categories: one falling very near 0 mm SMD, and another category ranging from c. 20 to 40 mm SMD. Consequently, the correlation coefficients obtained from model calibration and testing were lower than those for the grassland model (Schulte *et al.*, 2005). It can be assumed that the reason for this is that the SMD crop model includes assumptions on input parameters (i.e., measured crop growth stages and associated crop coefficients) over and above the parameters listed in Table 1. Since this model is specialized for spring cereal crops, the crop growth stages and associated crop coefficients used may be different in reality, and therefore it is expected that model performance could be further improved by empirical determination of the input parameters for the timing of crop growth stages.

Reference-evapotranspiration for spring cereal crops and crop coefficient curve

An attempt to have an additional linearly interpolated "natural-regeneration growth-development" stage before K_c returns to 1, resulted in poor output predictions (data not shown). This may be due to the fact that a small amount of natural-regeneration growth can start establishing before the harvest of crops (usually after the crops have matured). Therefore a simplified crop coefficient curve is used, as discussed above.

Model verification

The total monthly values for potential evapotranspiration for crops (Eto_{crop}) showed that these were generally within the range of Irish values. This indicates generally satisfactory performance of the model under Irish conditions. The prediction of effective drainage is a particularly important output of the model for the prediction of soil moisture conditions and leaching events. The effective drainage output showed that the model provides generally satisfactory predictions.

Potential for model modification

The current model has good potential for simple modifications for different soil and crop types. It can be modified for different types of soil by directly using components for moderately drained and poorly drained soil from Schulte *et al.* (2005). In order to modify the current model for different types of soil, tension measurements under crop production conditions should be determined to enable model recalibration and testing. The Drain_{max} parameter would need to be calibrated for poorly and moderately drained soils. In addition the current model also allows modification for different crop types by using appropriate crop coefficients and crop growth stages.

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