PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Dynamic Land Capability Model: A Case History [and Discussion]

Reinder A. Feddes, Aad L. M. Van Wijk, E. M. Bridges, P. H. Nye and M. J. Goss

Phil. Trans. R. Soc. Lond. B 1990 **329**, 411-419
doi: 10.1098/rstb.1990.0183

Dynamic land capability model: a case history

REINDER A. FEDDES[1] AND AAD L. M. VAN WIJK[2]

[1] *Department of Hydrology, Soil Physics and Hydraulics, Wageningen Agricultural University, Nieuwe Kanaal 11, 6709 PA Wageningen, The Netherlands*
[2] *Division of Soil Physics and Soil Management, The Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen, The Netherlands*

SUMMARY

A computer simulation approach has been developed that quantifies land capability in terms of crop productivity under different conditions of climate, soil, drainage or irrigation and farm management. This model deals with: (i) the dates and number of days in spring when soil moisture content falls sufficiently to permit soil cultivation and sowing or planting (farm management aspect); (ii) duration of germination and time of emergence in relation to soil moisture and temperature; (iii), water uptake, development, growth and harvest of the crop; (iv) number and time of soil workable days available for the harvest of root crops in autumn (farm management aspect).

The model was applied to compute effects of land drainage (15 combinations of drain depth and distance) on the yield of potatoes and spring cereals growing during 30 years (1952–81) on eight different soil types in the Netherlands. The outcome of this study was used as a basis for a nationwide system for evaluating the effects of soil and drainage upon crop yields. The methodology of the integrated model approach can be applied in other climates for a variety of crops growing on different soil types. It can be used to evaluate not only drainage effects on yield, but also those of irrigation and soil improvement. The approach is applicable to land evaluation studies in general.

INTRODUCTION

Assessment of the capability for land can be interpreted as the evaluation of land performance when used for specified purposes. Such information is needed in the planning of both rural and urban environments, of agriculture, of forestry and of engineering applications.

The land capability for agriculture depends on such factors as climate, soil, soil water and nutrient regime, topography, etc. Methods have been developed that assess land capability for crop production (FAO 1976; Haans *et al.* 1984), but these are usually based on interpretations obtained from soil maps, climatic zones, farmer's experience and experts judgement, and are thus qualitative in nature.

During the past 15 years increasing effort has been put into the development of computer models that simulate in a dynamic way crop development and yield from inputs of soil and climatic data. Such models can be applied rather effectively in land evaluation procedures to quantify crop productivity potentials (see, for example, Van Wijk & Feddes (1982, 1986); Van Lanen *et al.* (1989)).

This paper focusses on a model approach that predicts effects of changes in water management by drainage on farm management and crop yield.

Drainage of agricultural fields by furrows, ditches and pipe drains is a common measure to remove excess water. The excess may result from abundant rainfall, from irrigation or from seepage. When speaking about excess water one usually thinks of waterlogged conditions, i.e. visible inundation. In agriculture, however, even when there is no visible inundation the water content may still be too high in spring to permit access and workability of the soil. Sowing or planting time and emergence date will then be retarded and crop yields depressed. Transpiration, growth and dry matter production of crops, can be adversely influenced by the soil being either 'too wet' or 'too dry'.

The model approach was applied to derive criteria for the design of optimal drainage systems for growing arable crops on major soils in the Netherlands. Results are presented for potatoes and cereals over a 30-year (1952–81) period on eight different soils with fifteen combinations of drain depth and distance between drains.

MODELLING SOIL AND MOISTURE REGIME, SOIL UTILIZATION CONDITIONS, CROP GROWTH AND PRODUCTION

A model that simulates effects of water management on crop production has to consider effects of the soil being either too wet or too dry. Such a model should be capable of showing how soil moisture conditions in winter, time of tillage, germination and emergence in spring, crop development and production in summer and soil workability in autumn depend on drainage. Figure 1 shows a flow chart of an integrated approach for simulating these phenomena.

With the model FLOWEX (Wind 1979; Van Wijk 1987) (figure 1) the terms of the water balance of an

Phil. Trans. R. Soc. Lond. B (1990) **329**, 411–419
Printed in Great Britain

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

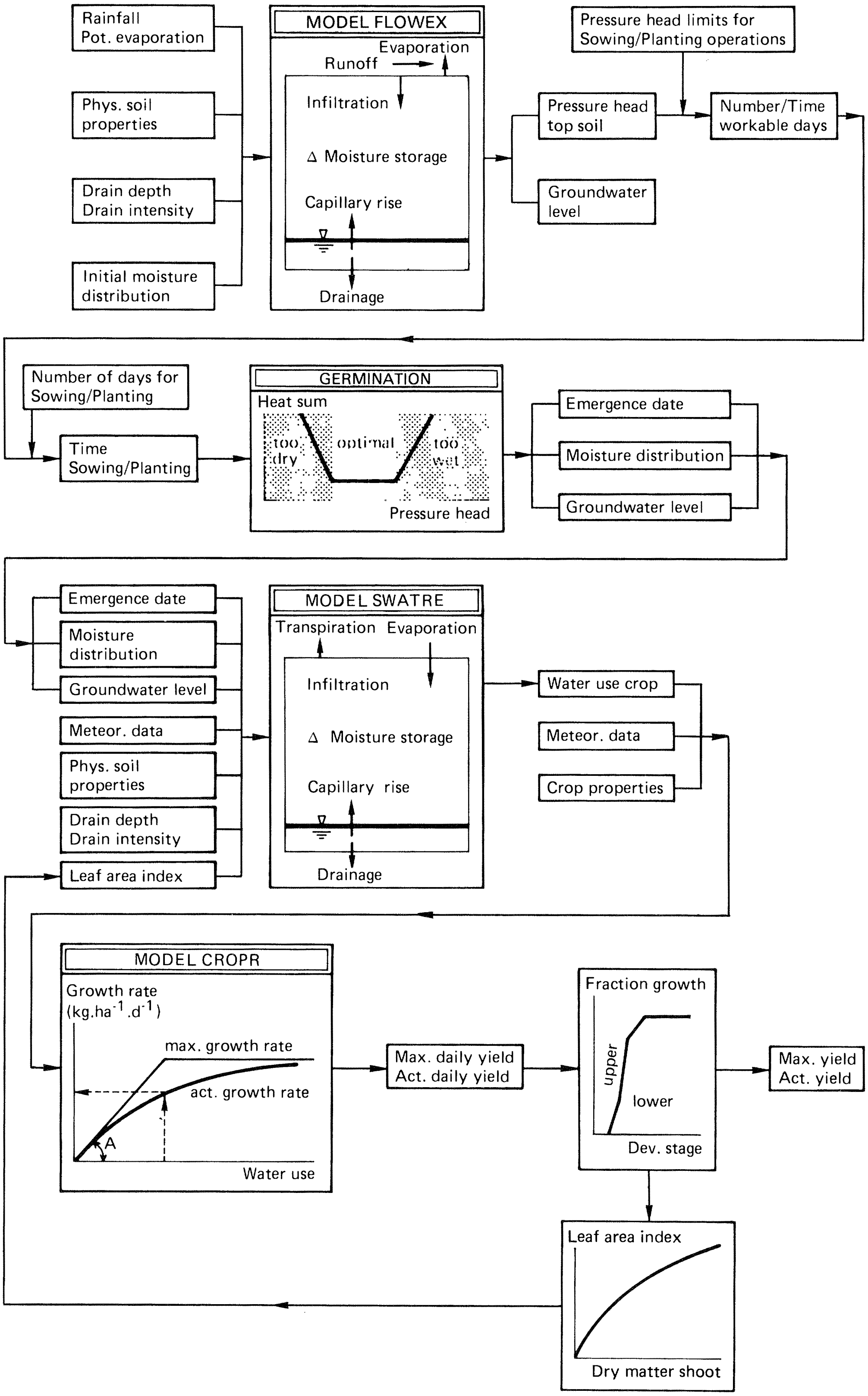

Figure 1. Flow chart of the integrated model approach for computing the influence of water management on yields of arable land.

uncropped soil are computed. Input data for this model are: precipitation rate, potential evaporation rate, soil moisture retention and hydraulic conductivity curves, drain depth and distance between drains and the initial soil moisture distribution down the soil profile. The main outputs of the model are the soil water pressure head at 5 cm depth and the groundwater table depth.

The soil moisture conditions in the top layer determine the working conditions. Soil water pressure head limits that are critical for workability were obtained from field experiments (Van Wijk & Feddes

1986; Van Wijk & Buitendijk 1988). With the aid of these limits one is able to derive the time and the number of days that the soil is workable from a day to day simulated course of the pressure head at 5 cm depth. Knowing the earliest possible sowing or planting date and the number of days required for these operations the time of sowing or planting can be predicted.

Knowing the sowing or planting date the emergence date can be predicted from information on the dependence of germination on soil water content and temperature in the seedbed. From field experiments relations between the heat sum needed for emergence, based on daily mean air temperature and the soil water pressure head in the seedbed were established for different crops (Van Wijk & Feddes 1986). Starting at the sowing date the heat sum required for emergence can then be computed according to these relations, with inputs of the 24-h mean air temperature and the daily simulated pressure head at 5 cm depth in the seedbed. From the emergence date the model SWATRE (Feddes *et al.* 1978; Feddes 1987; Feddes *et al.* 1988) starts the calculation of the components of the water balance of the cropped soil, taking into account an extra term for the water uptake by roots. This last term integrated over the rooting depth gives the transpiration rate of the crop. SWATRE uses as the initial condition, on the emergence date, the moisture distribution with depth as well as the groundwater table computed by FLOWEX.

The transpiration rate as computed by SWATRE creates together with the meteorological data and crop properties the input for the crop production model CROPR (Feddes *et al.* 1978). This model computes, for optimal nutrient conditions, both the potential and actual dry matter production rate of the crop. CROPR is based on an hyperbolic relation between growth rate and water use, bounded by two asymptotes: the maximum water use efficiency as derived from field water balance experiments. The horizontal asymptote represents the maximum possible growth rate which is computed from the photosynthesis rate taking into account solar radiation, leaf area index, air temperature, maintenance and growth respiration. The second asymptote represents the daily increase of the dry matter production which is distributed over upper and underground parts of the plants according to the development stage. From the total amount of leaves plus stems a new leaf area index is generated. This new index is the starting point for the computation of transpiration or production for the next day. The procedure continues until the day of harvest.

SOILS, CROPS, DRAINAGE AND WEATHER CONDITIONS USED IN THE SIMULATION

Eight major soil types were selected covering more or less the range of soils occurring in the Netherlands. They are shown in table 1. In the model these soils were subjected to fifteen different drainage regimes realized by varying the depth and the distance of the drains. The drain depths chosen were 60, 90, 120, 150 and 180 cm from the soil surface.

Table 1. *Selection of the eight major soil types of the Netherlands used in this study*

number	soil type	some characteristics
1	humous sand	40 cm humous sand over very fine poor sand
2	loamy sand	50 cm humous loamy very fine sand over poor sand
3	peaty sand	20 cm peaty sand over poor sand
4	silty loam	calcareous
5	sandy loam	calcareous
6	loam	40 cm calcareous loam over clayey fine sand
7	silty clay loam	70 cm silty clay loam over sandy loam
8	silty clay	calcareous

Each of these drain depths were combined with three different drain spacings ranging from narrow, medium, wide. These correspond with high, medium and low drainage intensities, respectively, in ratios of 4:2:1.

The influence of drainage on water management and crops depends heavily on the governing weather conditions. This implies that field drainage experiments have to be continued for a number of years, covering the entire range of climatic variations. The same holds true for numerical drainage experiments by simulation on the computer. In this study a period of 30 years of weather data (1952–81) of the meteorological station De Bilt in the Netherlands was selected. A statistical analysis showed that this sequence of years is of sufficient length to be representative and represents a normal distribution of wet and dry years. The crops selected were potatoes and spring cereals, being two major crops in the Netherlands of which sufficient data were available for use in the models.

The physical properties of the eight soils were determined in the laboratory on undisturbed soil samples. To calibrate and verify the models, data on weather, soil and crop were collected during two years from experimental field plots located on the eight selected soil profiles.

EFFECTS OF DRAINAGE ON CROP PRODUCTION SHOWN WITH POTATOES GROWN ON SANDY LOAM BASED ON 30 YEARS OF SIMULATION

Drainage, workability and planting time

Figure 2 shows the number of days that are available between 20 March–31 May for planting potatoes at two different drain depths. At the 60 cm drain depth there are years (1969 and 1973) without workable days before the end of May. Increasing the drain depth from 60 cm to 120 cm greatly increases the number of workable days; in very wet years (1965) there is a 100% probability that thirteen or more workable days occur between 20 March and 31 May. The average of the first four workable days occurring in spring is considered to be the planting date of potatoes.

Introducing deeper drains appears to be a very effective way of inducing earlier emergence (figure 3).

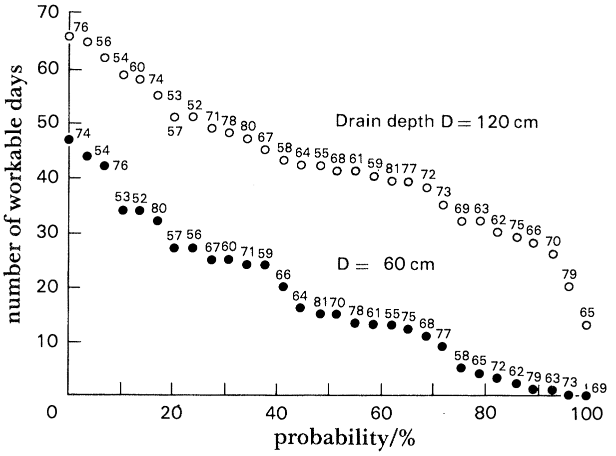

Figure 2. Model computation of the probability that a number of workable days for potato planting is exceeded in the period 20 March to 31 May. A workable day is defined as a day with a soil water pressure head at 5 cm depth not exceeding −100 cm. The relations refer to a sandy loam soil drained at depths of 60 and 120 cm. Each point represents one year out of the period 1952–81. Going from the right to the left, the 30 years are arranged in order of few to many workable days.

Going from a drain depth of 60 to 90 to 120 to 150 to 180 cm advances the 30-year averaged emergence date by 10, 21, 24 and 25 days, respectively. These figures show that the advancement of emergence date increases in a diminishing way with drain depth and there is little advancement by increasing the depth of drain from 120 to 180 cm. Larger drain depths are in general associated with deeper ground-water tables, hence with less capillary rise from the groundwater and thus a more rapid drying of the topsoil.

The relation between planting date and the time interval between planting and emergence date is given in figure 4. Early planting (30 March) results in an interval before emergence of 30 days, while late planting (9 May) at higher mean temperatures results in an interval of 15 days. Deferring the planting date from 30 March until 9 May will still result in later emergence.

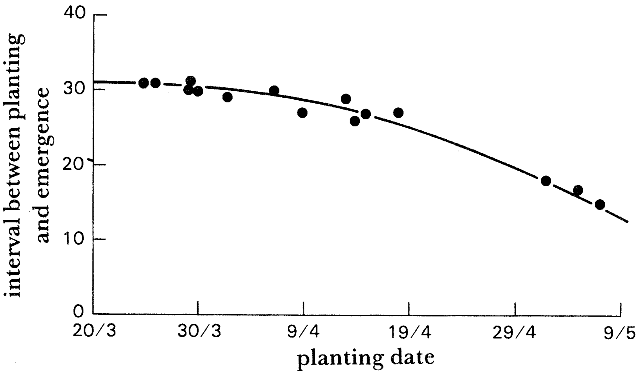

Figure 4. Interval between planting and emergence of potatoes in relation to the planting date as obtained from simulations over the period 1952–81 for a sandy loam. Each point represents one out of the fifteen combinations of drain depth and drainage intensity.

Figure 5 gives a summary of 30-year averages of the emergence date as a function of drain depth and three different drainage intensities. Both depth and intensity strongly influence the earliness of emergence of potatoes, but the effect of drain depth is more pronounced. Increasing the drain depth from 60 to 150–180 cm advances the emergence date by about three weeks.

The model also enables the effects of time of emergence on final crop yield to be quantified. First confine attention to spring-only effects on growth. The model calculates crop production with an optimal

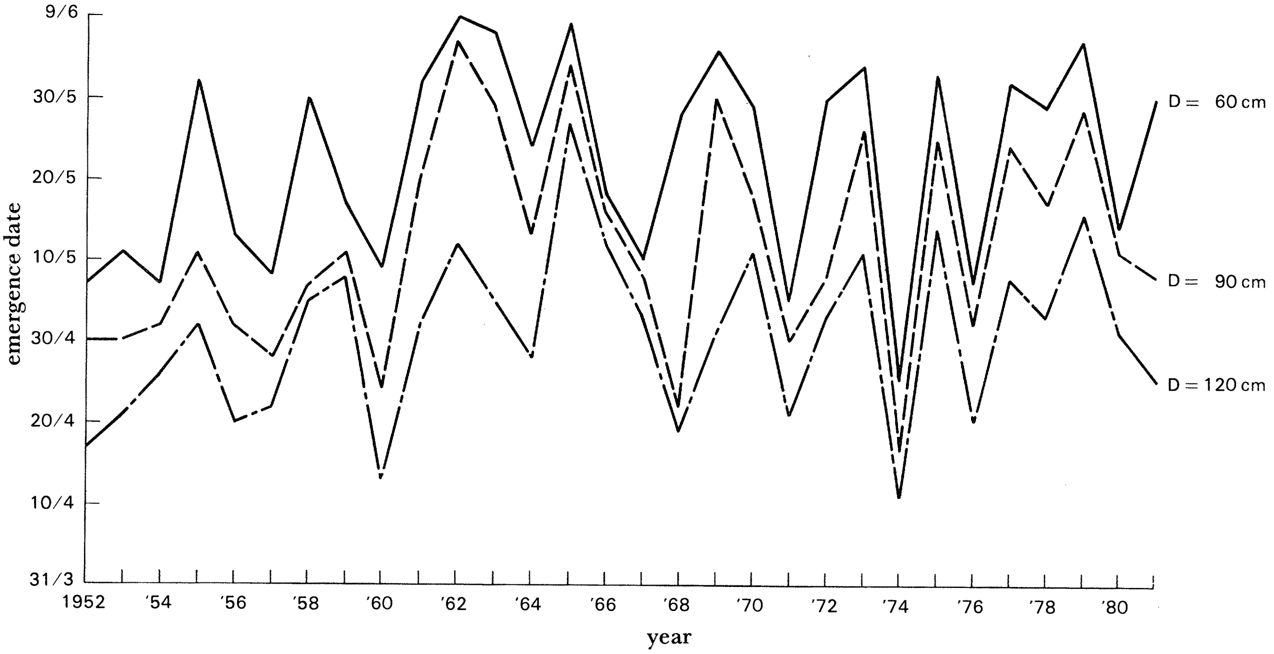

Figure 3. Yearly emergence dates of potatoes on a sandy loam simulated over the period 1952–81 at three different drain depths with comparable drainage intensities.

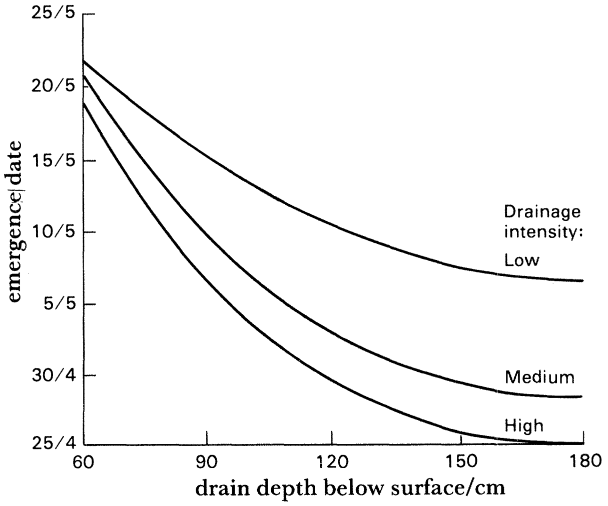

Figure 5. Influence of drain depth and drainage intensity on the emergence date of potatoes growing on a sandy loam based on a simulation over the period 1952–81. Three drainage intensities are considered.

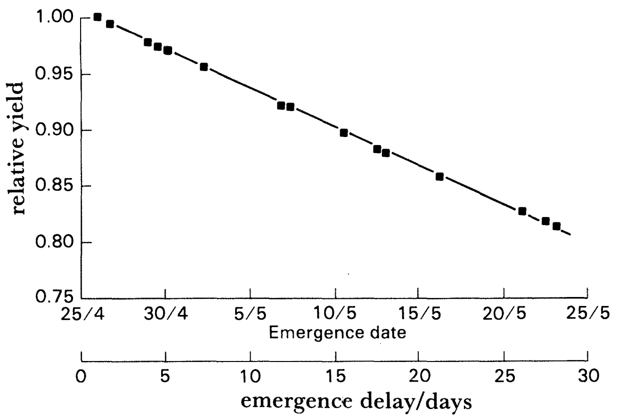

Figure 6. Influence of emergence date/emergence delay on relative yield of potatoes on sandy loam based on 30-year averages (1952–81) for fifteen drainage combinations.

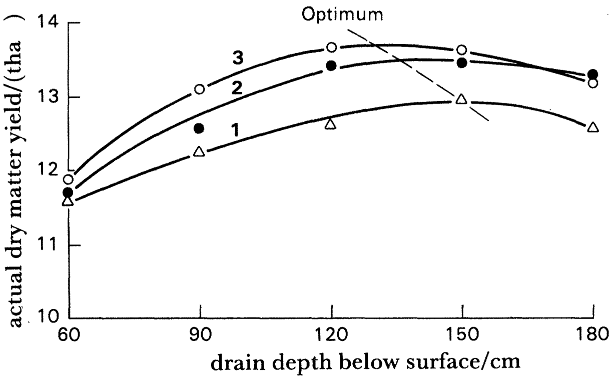

Figure 7. Actual dry matter yield of potatoes as a function of drain depth at three drainage intensities based on 30-year averages (1952–81). 1, low drainage intensity; 2, medium drainage intensity; 3, high drainage intensity.

water supply during the growing season. A result of such a calculation is shown in figure 6. Under the conditions in the Netherlands the emergence date is between 26 April and 23 May. The figure shows that in the period April–May each day's delay in emergence causes 0.7 % loss in yield.

In conclusion, inadequate drainage generally results in a decrease in accessibility, trafficability and workability of the soil and thus in a delay of planting and emergence date. Hence the length of the growing season is reduced and consequently crop yield will be lower than under optimal conditions of drainage. Moreover, if farming operations are carried out when the conditions are too wet there will be soil compaction and more soil degradation. In addition operations have to be carried out over a shorter period, which can place a difficult-to-meet demand on labour and machinery.

Drainage, crop transpiration and production

Once the emergence date is known, which is different for each year and drainage combination, crop transpiration and production can be computed according to the procedure described in figure 1. From figure 7 it can be seen that there is a clear effect of drain depth and drainage intensity on crop yield. The optimal drain depth for this soil is between 130 and 150 cm. The maximum yield is obtained at the high drainage intensity (curve 3). The dry matter yield obtained at the medium drainage intensity (curve 2) however, is only 2 % smaller, with half the drainage intensity. The dry matter yield of curve 3 is about 6 % greater than that of curve 1, near the optimum drain depth of 130 cm, despite a fourfold difference in drainage intensity. To finally decide, however, on the optimal combination of drain depth and drainage intensity would need an economic analysis.

The effects of drainage on yield are divided into a component for the influences of drainage that occur in spring (workability, timeliness, earliness) and for those that occur during the remainder of the growing season (water supply) (figure 8). The total effect is obtained in multiplying the two components. The vertical lines in figure 8 show the variation in relative yield due to differences in drainage intensity. The effect of drainage in spring is most pronounced; an 18 % yield reduction with a drain depth of 60 cm compared with that at 180 cm. To prevent yield reduction due to delayed workability and emergence, this sandy loam soil needs a drain depth of 150 to 180 cm. The yield reduction due to water shortage in the growing season amounts to about 8 % at a drain depth of 180 cm compared with that at 60 cm. When both the spring and summer effects are taken into account the optimal drain depth is 130–140 cm. For this sandy loam the main cause of yield reduction is a delay in workability and emergence in spring.

EFFECTS OF DRAINAGE ON YIELD OF POTATOES AND SPRING CEREALS GROWN ON EIGHT SOIL TYPES

Effects of drainge on yield of potatoes and spring cereals grown on the eight soil types can be quantified in the way described in the preceeding section for

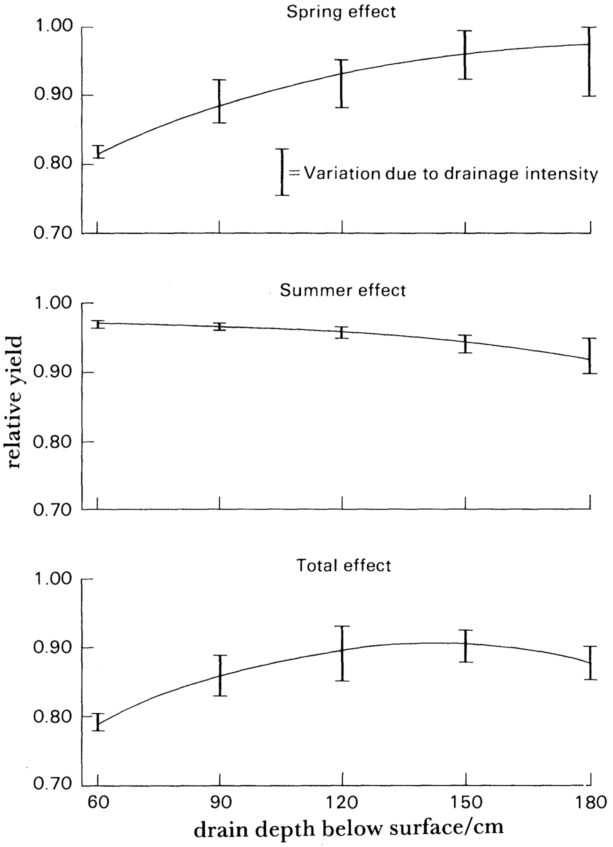

Figure 8. Relative yield of potatoes growing on a sandy loam averaged over 30-year (1952–81), presented as drainage effects occurring in spring, summer and the total season.

potatoes on a sandy loam. In the following we consider the 'spring' and 'remainder of growing season' components of the effect on yield. We also consider the combination of both components.

Potatoes

Figure 9 shows the effect of drain depth on the spring component of relative yields of potatoes for high drainage intensity. Because of delays in emergence, the largest yield deficit (compared with the potential maximum) occurs at drain depths of 60 and 90 cm in the sandy and loamy soils (soil types nos. 1–5). These effects are less pronounced on the loam soil (no. 6) and are almost absent on the silty clay loam (no. 7) and the silty clay (no. 8). To avoid late planting and the consequent suboptimal yields, the drain depth should be approximately 150–180 cm at a high drainage intensity. In considering figure 9 however, it must be born in mind that factors other than those that occur in spring need to be taken into account in assessing the various soil types. Of special importance is the moisture supply during the growing season.

The general trend of the curves in figure 10 is for yields to decrease with increase in drain depth. The largest damage due to water shortage because of too great a drain depth occurs on the peaty sand (soil type no. 3). Also susceptible to drought is the humous sand (no. 1). The heavier textured soils show only a slight response on drain depth. Loamy sand (no. 2), silt loam (no. 4), sandy loam (no. 5) and silty clay loam (no. 7) react in an identical way.

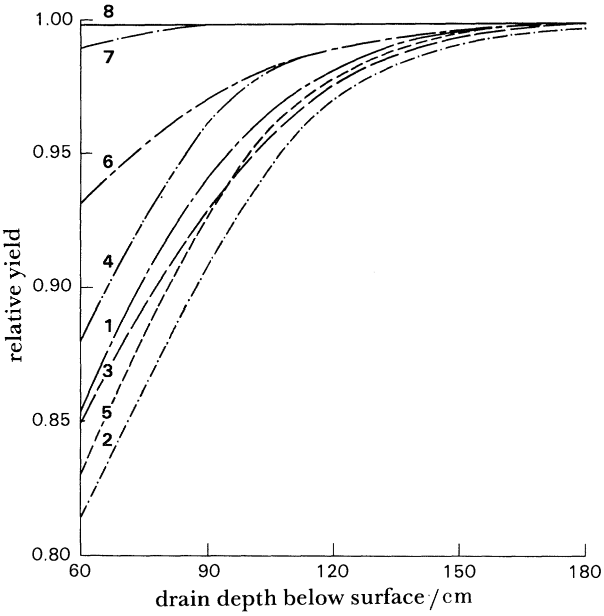

Figure 9. Decrease in relative yield of potatoes due to soil conditions being too wet and workability/emergence being delayed in spring in relation to drain depth for eight soil types (nos. 1–8). Results are based on 30-year simulations (1952–81) at the high drainage intensity.

From the simulations it appears that when the drainage conditions are optimal both in spring (earliest possible sowing and emergence date) and also in summer (no water shortage), differences in yield still occur between the eight soil types. These differences are caused by differences in earliness in spring which are independent of the drainage conditions. Because of

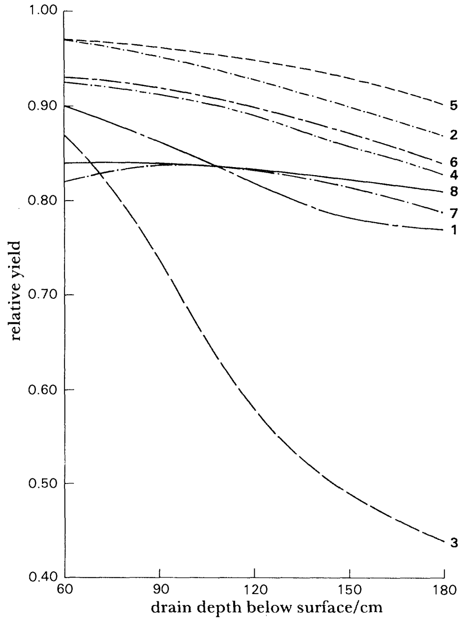

Figure 10. Decrease in relative yield of potatoes due to moisture shortages during the growing season in relation to drain depth for eight soil types (nos. 1–8). Results are based on 30-year simulations (1952–81) at the high drainage intensity.

Table 2. *Differences in relative yield of potatoes between the eight soil types because of differences in earliness in spring*

profile number	1	2	3	4	5	6	7	8
relative yield	0.98	1.00	0.98	0.99	0.99	0.97	0.96	0.90

more favourable soil physical properties the one soil type reaches, by faster drying, the soil moisture limits required for proper workability in spring earlier than the other. This behaviour leads to a lengthening of the growing period and thus to a higher crop production. Table 2 shows this so-called 'soil type' effect. The soil types nos. 1–5 show little difference in yield. As the soils become heavier in texture (nos. 6–8) larger yield reduction occurs (up to 10% for profile no. 8) because of a delay of planting owing to the soil being too wet.

Figure 11 shows the total effect of drainage on yield of potatoes for the high drainage intensity. The total effect is composed of the spring component (figure 9), summer component (figure 10) and soil type component (table 2). A relative yield of 1 is never reached, because figure 11 pertains to 30-year averages.

From figure 11 we can conclude the following:

(i) the optimal drain depth values from about 90 cm (soil type no. 3) to about 130–140 (no. 5);

(ii) the effect of the soil being too wet is most pronounced at the soil type nos. 2 and 5. Increasing the drain depth from 60 to 90 and to 120 cm results in the relative yield increasing from about 0.78 to 0.84 to about 0.90. These soils have the highest hydraulic conductivity. The larger the conductivity the larger the capillary supply from the groundwater table to the soil surface. In the case of a shallow groundwater table depth (i.e. shallow drain depth) the evaporation from the soil surface can easily be met by the supply from below, and thus the moisture conditions in the top soil in spring remain relatively wet. Increasing the depth of drainage increases the distance between the soil surface and the groundwater table and reduces capillary rise;

(iii) the heavier soils (soil type nos. 6, 7 and 8) have a lower hydraulic conductivity and hence the response to increasing drain depth is less pronounced;

(iv) the effect of the soil being too dry (yield reduction at greater drain depths) is most pronounced on soil type no. 3;

(v) in the case of the other profiles the effect of the soil being too dry is much less: 1–3% in the range of 120–180 cm.

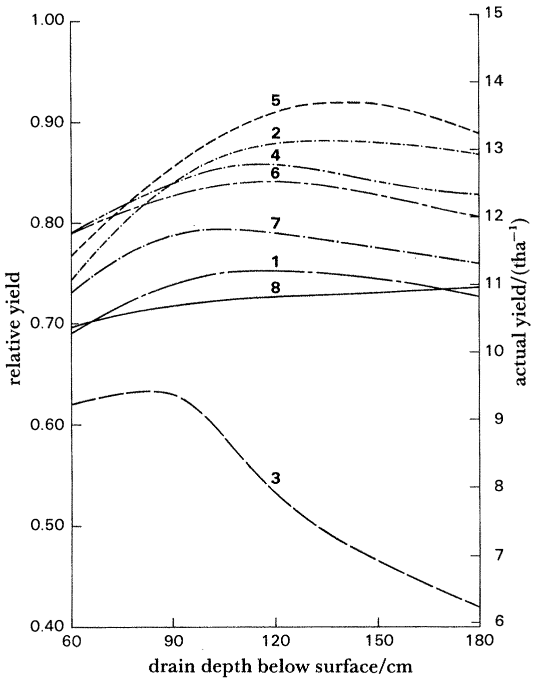

Figure 11. Reduction in total relative yield of potatoes as a result of soil conditions in spring being too wet, water shortage during the growing season and differences in earliness between the soils in relation to drain depth for eight soil types (nos. 1–8). The actual yield is also shown.

Spring cereals

Spring cereals differ markedly from potatoes in respect of soil workability (less demanding), sowing date (earlier), crop habitat, ripening, harvest time (earlier). The total effect of drainage on the yield of spring cereals has been calculated in the same way as described for potatoes. The final result is shown in figure 12. Comparison with figure 11 shows the following:

(i) to prevent restricted yield from the soil being too wet in spring, the drain depth should be at least 90 cm, which is for most soils less deep than for potatoes;

(ii) cereal yields are less dependent than those of potatoes on drought conditions resulting from greater drain depths. The reasons for this are the greater rooting depth of cereals (more available water) and the growing period being generally wetter (potatoes unlike cereals are still growing in August by which time high soil moisture deficits have generally developed).

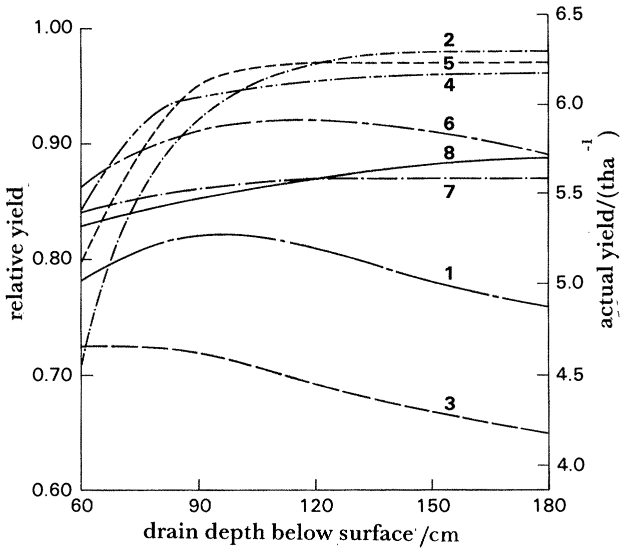

Figure 12. Reduction in total relative yield of spring cereals because of soil conditions being too wet in spring, water shortage during the growing season and differences in earliness between the soils in relation to drain depth for eight soil types (nos. 1–8). The actual yield is also shown.

REFERENCES

Food and Agriculture Organization 1976 *A framework for land evaluation*. (87 pages.) (*Soil Bull.* 32) Wageningen, The Netherlands: International Institute for land reclamation and improvement.

Feddes, R. A. 1987 Simulating water management and crop production with the SWACRO-model. In *Proceedings of the third international workshop on land drainage*, pp. 27–40. Columbus, Ohio: Ohio State University.

Feddes, R. A., de Graaf, M., Bouma, J. & van Loon, C. D. 1988 Simulation of water use and production of potatoes as affected by soil compaction. *Potato Res.* **31**, 225–239.

Feddes, R. A., Kowalik, P. J. & Zaradny, H. 1978 Simulation of field water use and crop yield. In *Simulation monographs* (189 pages). Wageningen, The Netherlands: PUDOC.

Haans, J. C. F. M., Steur, G. G. L. & Heide, G. 1984 Progress in land evaluation. In *Proceedings of the seminar on soil survey and land evaluation*. (309 pages.) Wageningen, 26–29 September 1983. Rotterdam, The Netherlands: A. A. Balkema.

van Lanen, H. A. J., Bouma, J. & van Randen, Y. 1989 Mixed qualitative/quantitative land evaluation procedure. In *Agriculture. Application of computerized EC soil map and climate data* (ed. H. A. J. van Lanen & A. K. Bregt), pp. 11–20. Proceedings of the EC-workshop, Wageningen, 15-16 November 1988. Report EUR 12039 EN. Commission of the European Communities, ECSC-EEC-EAEC, Brussels, Luxembourg.

van Wijk, A. L. M. 1987 Modeling the effects of drainage and soils on workability of arable land and on bearing capacity of pasture. In *Proceedings of the third international workshop on land drainage*, pp. 139–151. Columbus, Ohio: Ohio State University.

van Wijk, A. L. M. & Buitendijk, J. 1988 A method to predict workability of arable soils and its influence on crop yield. *Catena Suppl.* **11**, 129–140.

van Wijk, A. L. M. & Feddes, R. A. 1982 A model approach to the evaluation of drainage effects. In *Land drainage* (ed. M. J. Gardiner), pp. 131–151. Proceedings of the EEC-seminar, Cambridge, U.K. Rotterdam, The Netherlands: A. A. Balkema.

van Wijk, A. L. M. & Feddes, R. A. 1986 Simulating effects of soil type and drainage on arable crop yield. In *Agricultural water management* (ed. A. L. M. van Wijk & J. Wesseling), pp. 97–112. Proceedings of the symposium on agricultural water management, Arnhem, 18–21 June 1985. Rotterdam, The Netherlands: A. A. Balkema.

Wind, G. P. 1979 Analog modeling of transient moisture flow in unsaturated soil. In *Agricultural research report* No. 894 (54 pages). Wageningen, The Netherlands: PUDOC.

Discussion

E. M. BRIDGES (*University of Wales, Swansea, U.K.*). After commenting that the Netherlands had no soil, only sediments, the question was asked if the model could take into account impervious layers at shallow depth. Many British surface-water grey soils have water held between 15 and 30 cm depth and would not be effectively drained by the drains at 90–120 cm.

R. A. FEDDES. The model is able to take into account impervious layers at shallow depth indeed. The disturbing presence of this poorly permeable layer would result in the simulations in regular waterlogged conditions and a delay of field operations in spring.

M. J. GOSS (*The Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen, U.K.*). In a lysimeter study with winter wheat at the Letcombe Laboratory the optimal drainage depth was 0.5 m. Will Dr Feddes comment on the difference between the result for an autumn-sown crop and the predictions for spring crops from his model.

R. A. FEDDES. I discussed results of drainage on potatoes and spring wheat in relation to moisture conditions in spring (time of tillage, germination and emergence) as well as in summer (water supply). Dr Goss's lysimeter experiment deals *de facto* with water supply only. Considering the water supply we reach similar results for spring wheat as for potatoes (see figure 10), i.e. highest yield at shallow drain depth. In addition to water supply the conditions for tillage and sowing have also to be taken into account. When doing so, the optimum drain depth changes towards greater depths (see figure 12). The latter effect is most pronounced on the lighter textured soils (see figure 9).

P. H. NYE (*Department of Plant Sciences, University of Oxford, U.K.*). Plant physiologists devote much time and effort to finding out why crops grow poorly in badly drained sites. What contribution do you think they can make to the further development of your model?

R. A. FEDDES. When soil moisture content is high, the gas exchange between soil and atmosphere is often low, causing oxygen deficiency. Root respiration and root volume are reduced, the resistance to water and nutrient transport increases and toxic compounds can be found in soil as well as in plants.

I would like the plant physiologists to answer the following questions: (i) what is the oxygen demand of a crop under various environmental conditions during the various growing stages, i.e. how much oxygen at which time is required? This holds especially true under conditions of high activity of the plant at critical growing stages (e.g. flowering) and environmental conditions (e.g. high temperatures). (ii) What is the damage done to root respiration when the oxygen demand of the crop cannot be met by the oxygen supply due to a too high wetness of the root zone? (iii) The same holds for the damage done to the root mass. (iv) How does soil aeration influence the uptake of water and nutrients by plants?

In the present version of the model inputs are needed about the two critical soil water pressure heads in between which the relative wate uptake increases from zero (anaerobiosis point) to 1 (optimal oxygen supply). In addition, the variation of the depth of the root zone with time is needed.

Dr M. J. GOSS. In poorly drained land root growth depends on the oxygen flux reaching the roots. For oats and wheat a flux density less than 10 μg m^{-2} s^{-1} effectively stops root growth at 10 °C. In clay soils the small volumes of oxygen trapped as the soil wets up over winter can provide the necessary flux of oxygen to the roots over the winter period, but oxygen demand increases with the rise in temperatures in spring (Blackwell & Ayling 1981). As well as affecting root growth limiting oxygen supply will have important effects on nutrient availability especially in removing nitrate-nitrogen by denitrification.

Reference

Blackwell, P. S. & Ayling, S. M. 1981 Agricultural Research Council, Letcombe Laboratory Annual Report 1980, pp. 35–38.

R. A. FEDDES. I agree with your comment.

D. J. GREENWOOD (*AFRC, Institute of Horticultural Research, Wellesbourne, Warwick, U.K.*). I would like to comment a little further on the effects of transient water-logging on crop growth. I quite agree that temperature is of critical importance: the higher the temperature the greater the damage. But also the stage of growth can be of much importance. For instance a single days water-logging at the time of flowering of peas had a devastating effect on yield but had little effect when imposed at other stages of growth e.g. Proc 7th int Congr Soil Sci., **3**, 478. A somewhat similar effect has been reported for cereals e.g. Soils & Fert. **28**, 370. I also think the importance of the ability of crop roots to transmit oxygen along them (e.g. New Phytol., **66**, 337 and **70**, 85 may have been underestimated. Another factor of considerable importance is the way some plants can withstand water logging by carrying out anaerobic respiration without the production of harmful products whereas in other species anaerobic respiration produces highly phyloloxic products e.g. J exp. Bol., **19**, 133 and J. Ecol., **37**, 235 that kill the plant.

R. A. FEDDES. Thank you for your additional comment.

A. C. ARMSTRONG (*Adas Field Drainage Experimental Unit, Trumpington, U.S.A.*). The present model accounts for soil heterogeneity because of layers having different hydraulic properties, i.e. the soil moisture retention and hydrualic conductivity curves.

Non-homogeneous water movement through soils due to macropores and swelling or shrinkage cracks can be modelled in the way as shown by Bronswijk (1988). In his paper a general method is outlined to develop simulation models for the calculation of water balance, subsidence and crack volume of clay soils. In this method the shrinkage characteristic is introduced as a third soil-water function besides the water retention curve and the hydraulic conductivity curve. By introducing shrinkage characteristics in simulation models, a clay soil may be considered a continuously changing configuration of soil matrix and shrinkage cracks. This allows a dynamic partition of rainfall into matrix and crack flow, calculation of bypass flow, adaption of layer thickness over which Darcy fluxes can be calculated and calculation of cracks and subsidence of the soil.

The success of the soil water component of Dr Feddes model depends to a large degree on the extent to which the soil can be represented as a homogenous medium. However, as we have become increasingly aware, many soils are not homogeneous, and in particular often contain preferred routes for soil water movement, which are generally called 'macropores'. Can you please show how your model might be adapted to encompass such variability?

The model assumes that the farmer using the soil is able to plant his crops at the earliest possible date. In real farming situations this is never possible, because farmers have whole farms to manage, which cannot normally be planted all in one day. Because of this, farmers will be forced to plant after the earliest possible date, and may even be forced to plant before the soil is in a suitable condition. Your model could, if required, take into account the sub-optimal late sowing, by reference to the relation between date of sowing and final yield. However, use of this relationship would not be possible for premature sowing, since there is no function to take into account the damage to the soil physical environment, and hence the eventual yield penalty. Could Dr Feddes speculate how he might incorporate such a function into his model?

Reference

Bronswijk, J. J. B. 1988 Modeling of water balance, cracking and subsidence of clay soils. *J. Hydrol.* **97**, 199–212.

R. A. FEDDES. Your question is possibly based on some misunderstanding of the model approach. Good workability refers not only to soil conditions, but also to a time in spring as close as possible to the optimum sowing or planting date. For the Netherlands this date was derived from sowing time experiments and is for spring cereals 1 March and for sugar beets and potatoes 20 March. Knowing these optimum sowing or planting dates and the number of days required for these operations we can predict the time of sowing or planting. At the present level of mechanization the farmers in the Netherlands use one and two days for sowing spring cereals and sugar beets, respectively, and four days for planting potatoes. Hence, for planting potatoes the first four days that are workable are used. These days do not necessarily have to occur as a consecutive series of days. The model accounts of non-workable days.

The influence of structure on yield on poorly drained soils is included in the results by having the 'model' farmer sowing only when the required tension for tillage is actually reached. In practice the farmer will not always wait that long, but will risk deterioration of structure and the yield depression that it causes. This depression was assumed to be of the same magnitude as the one that the 'model farmer' incurs when he delays sowing.