Irish Journal of Agricultural Research **27**: 167-178, 1988

Drumlin Soils — The Depression of Herbage Yield by Shallow Water Table Depth

A. J. Brereton and M. Hope-Cawdery[1]
An Foras Talúntais, Johnstown Castle Research Centre, Co. Wexford

Abstract

The objective was to develop a quantitative framework for the evaluation of water table effects on herbage growth in wet soils. Over a period of 5 years, growth and water table depth was measured weekly. The effect of shallow water table depth in depressing growth was estimated by comparing measured growth and growth expected in well-drained conditions (using a growth model). Measured growth expressed as a fraction of the expected growth (R) was related to water table depth (W) by $R = -0.3643 + 0.002977W$. Soil dry matter content (and trafficability) was related to water table depth also. A model is presented which estimates water table depth as a function of rainfall and evaporation.

There was considerable interyear variability in water table effects and it was concluded that production systems on wet soils need to be managed flexibly in order to maintain efficiency.

Introduction

The purpose of this paper is to provide a quantitative framework for the evaluation of the effect of water table depth on herbage yield in the wet mineral lowland soils of Ireland. These soils occur extensively. They occupy almost 0.30 of the land area. They occur mainly in western areas. The soil is usually a pseudogley with a perched water table overlying an impervious subsoil. The hydraulic conductivity of the subsoil is 2.4×10^{-2} mm per day (Mulqueen and Roche, 1975). The soils have been described in detail (Gardiner, 1973, Appendix).

This study is based on data from Ballinamore, Co. Leitrim. Previous studies at Ballinamore (Burke, Mulqueen and Butler, 1974; Mulqueen, 1985) have shown that when water table depth was increased, annual herbage yield increased by between 1.1 and 1.3 approximately. It was concluded that herbage yield was affected when the water table depth was less than 370 mm, mainly in spring/early summer, though effects were recorded throughout the growing season. The herbage yield response to changes in water table depth was greater at lower, compared to higher,

[1]An Foras Talúntais, Grange Research Centre, Dunsany, Co. Meath.

levels of N use and was also affected by the species composition of the sward.

Because these wet soils occur extensively in Ireland, there is an urgent need for a quantitative understanding of the relations between herbage yield, its seasonality, soil conditions and weather so that optimal management strategies can be developed.

In this study the approach adopted was to monitor herbage yield restriction due to waterlogging at weekly intervals throughout the season in perennial ryegrass dominant swards with relatively high rates of mineral fertiliser application. The herbage yield restriction due to waterlogging was measured in terms of the ratio of harvested yield and the yield expected for a well-drained soil. Expected yield was calculated as a function of weather using a growth model. A simple water balance model was assembled to estimate water table depth as a function of evapotranspiration and rainfall.

Methods

The study was carried out at the research station at Ballinamore, Co. Leitrim on an undrained site in the meteorological compound.

In March 1982, twelve microplots were marked out in a rectangle of 6 × 2 plots to form 3 blocks of 4 plots each. The plots were square (1.0 m side) and each was surrounded by a 0.5 m strip of bare soil. A dipwell was installed in the centre of each block. The dipwell was of gunbarrel pipe, 21 mm internal diameter with the open bottom resting on a shallow layer of sand. The pipe was perforated. The upper rim of the dipwell was 700 mm over ground, the bottom was 500 mm underground.

At the start of the experiment three plots in each block were dug over and reseeded with perennial ryegrass (var. Talbot) and in each subsequent year one of these was reseeded in rotation. The fourth plot in each block represented the old sward throughout the experiment although perennial ryegrass seed was broadcast over these in March 1982. The seed application rate was 60 kg ha^{-1}.

Prior to the start of the experiment limestone was broadcast at the rate 12.36 t ha^{-1} and compound NPK (0:10:20) at the rate 1.48 t ha^{-1}. In each year limestone was applied at the rate 2.5 t ha^{-1}, compound fertiliser (0:7:30) at the rate 0.9 t ha^{-1} and nitrogen fertiliser (0.275 N) at the rate 1.0 t ha^{-1}. The compound was applied in 3 applications — in May, July and September. The N fertiliser was applied in 5 applications between March and August.

Herbage yield was measured at weekly intervals from week 10 to 36 and at 2 or 4 week intervals outside this period. Each plot was harvested using an electric rotary mower fitted with a grass box. Water table depth in each dipwell was recorded as the plots were harvested. Additionally, the moisture content of the topsoil to 127 mm depth was measured in cores 25.4 mm in diameter.

Weather records were obtained on a daily basis at the site (a climate station of the national network using equipment and procedures approved by the meteorological service). Radiation was estimated from hours bright sun using the relationship given by McEntee (1980). Evaporation was measured using a class A pan.

The herbage growth model

The model described here has been tested by comparing model estimates of herbage growth with herbage growth measured directly in cutting trials or indirectly from animal output data (Ryan, Brereton and

O'Keeffe, 1984; Brereton, Hope-Cawdery and Harrington, 1987). The tests indicated that the model provided a satisfactory imitation of reality in temperate grass swards subject to periodic defoliation.

The model assumes that herbage growth is proportional to the radiation received at the crop surface (Penman, 1971). The efficiency with which the received radiation is converted to dry matter depends on current temperature.

$Y = eR/V$ ....Equation 1

where

Y = herbage dry matter accumulation rate (kg ha^{-1} day^{-1})

R = radiation (400-2000 nm) received at crop surface (MJ ha^{-1} day^{-1})

e = efficiency of conversion of radiation energy to herbage energy

V = energy content of herbage dry matter (assumed constant — 16.67 MJ kg^{-1}) (Golley, 1961).

The effect of temperature on the efficiency of conversion of radiation is given by the equations

$e = 0, T < 4.5$ ....Equation 2

$e = -0.008935 + 0.002037T$, $9.5 > T > 4.5$ ....Equation 3

$e = 0.003493 + 0.000702T$, $T > 9.5$ ....Equation 4.

It is necessary to introduce a factor reflecting the change in sward physiology in June which coincides with the change between the vernalised reproductive and the unvernalised vegetative state. The effect of this change is incorporated through a simple physiological index (x) which has the value 1.0 in the period from January 1 to May 31, varies linearly from 1.0 to 0.4 during June and has the value 0.4 after July 1. Equation 1 then becomes

$Y = eRx/V$ ....Equation 5.

The effect of soil moisture deficit is calculated as the fractional depression of the potential growth (growth in the absence of any water deficit) as a function of the soil moisture deficit.

Potential evapotranspiration (evapotranspiration in the absence of any water deficit) is calculated according to the relationship (Priestley and Taylor, 1972):—

$E_p = k\,Q\,(B/M)/((B/M)+1)$ ....Equation 6

where

k = an empirical constant (1.26)

Q = net short wave radiation (mm H_2O equivalent)

M = psychrometric constant

B = slope of the saturation specific humidity — temperature curve at air temperature.

Actual evapotranspiration is assumed equal to potential evapotranspiration at soil moisture deficits less than 40 mm. At greater deficits the ratio actual evapotranspiration:potential evapotranspiration declines linearly with increasing deficits and at 120 mm the ratio is zero (Aslyng, 1965). Thus, for deficits exceeding 40 mm:—

$E_a/E_p = 1.5 - 0.0125\,S$ ....Equation 7

where

E_a = actual evapotranspiration (mm) and

S = soil moisture deficit (mm).

Actual evapotranspiration is calculated from —

$E_a = E_p\,(E_a/E_p)$ ....Equation 8.

The fractional depression of crop growth in drought conditions is proportional to the fractional depression of the evapotranspiration. The relationship between the growth ratio and the evapotranspiration ratio depends on the level of nitrogen used. For example the relationship appropriate to an annual rate of nitrogen (N) use of 240 kg^{-1} ha^{-1} is :—

$$Y_a/Y_p = 0.20 + 0.80\, E_a/E_p \quad \text{..........Equation 9}$$

$$Y_a = Y_p(Y_a/Y_p) \quad \text{..........Equation 10.}$$

A mean value of e is calculated for each day. Temperature is assumed to vary sinusoidally during each 24 hour period. The daily average value is calculated as the average of 24 hourly values. Hourly values of temperature (T) are obtained from the daily average temperature by —

$$T = \overline{T} + 0.5a \text{ Sin } (2 \times 3.14 \times H/24) \quad \text{..........Equation 11}$$

where

$\overline{T}$ = mean daily air temperature

H = hours after time of mean temperature

a = amplitude of diurnal range of air temperature $(5 + 0.2\overline{T})$.

It is assumed that the leaf area index appropriate to the operation of the model is relatively low — between 2 and 5 — and the light saturation of the canopy is relatively complete at a radiation flux density of 400 w m^{-2} (400-2000 nm). Radiation flux density (I) is assumed to vary sinusoidally during daylight hours (Charles-Edwards, 1981):—

$$I = 3.14L/2Z \text{ Sin } (3.14t/Z) \quad \text{..........Equation 12}$$

where

L = daily light integral (J cm^{-2} day^{-1})

Z = daylength (hrs)

t = time after sunrise.

The daily effective radiation used in the model is obtained by integration of the total radiation received at flux densities less than 400 w m^{-2}.

The water table model

The model was developed by successive trial simulations using the measured trends in water table depth at Ballinamore (see Results, Fig. 1) as a reference. The relatively impervious nature of the soil and its parent material (a sticky glacial till) gives rise to a perched water table and impeded drainage (Walsh, 1973). Previous work indicated that the natural rate of drainage at Ballinamore is negligible and that rainfall in excess of 2-5 mm d^{-1} is lost as surface run-off (Mulqueen, 1971; Mulqueen and Roche, 1975). Therefore it is assumed in the model that soil drainage rate is zero and that rainfall in excess of 3.0 mm day^{-1} is lost through run-off. Using these assumptions, it was found following successive trial simulations that agreement between observed and calculated trends in water table depth was good if two further assumptions were made, i.e. that one-third of the volume of soil at field capacity is occupied by available water and that the maximum water table depth from soil surface is 450 mm. The former assumption implies that the accumulation or depletion of 1 mm of water from the system causes the water table to rise or fall by 3 mm respectively. The latter assumption agrees with the observation of water table depth — 450 mm was the greatest depth recorded even in dry periods. However, this depth also coincided with the maximum depth of the dipwell.

The current depth to the water table (W) then is given by —

$$W = W_o + (E\text{-}P)\, 3 \quad \text{.......Equation 13}$$

where

W_o = water table depth at the end of the preceding week (mm)

E = total evaporation in the current week (class A pan, mm)

P = precipitation in the current week (maximum 21.0 mm)

Results

General review of weather and growth

The weather summary in Table 1 shows that 1985 and 1986 were wetter, cooler and

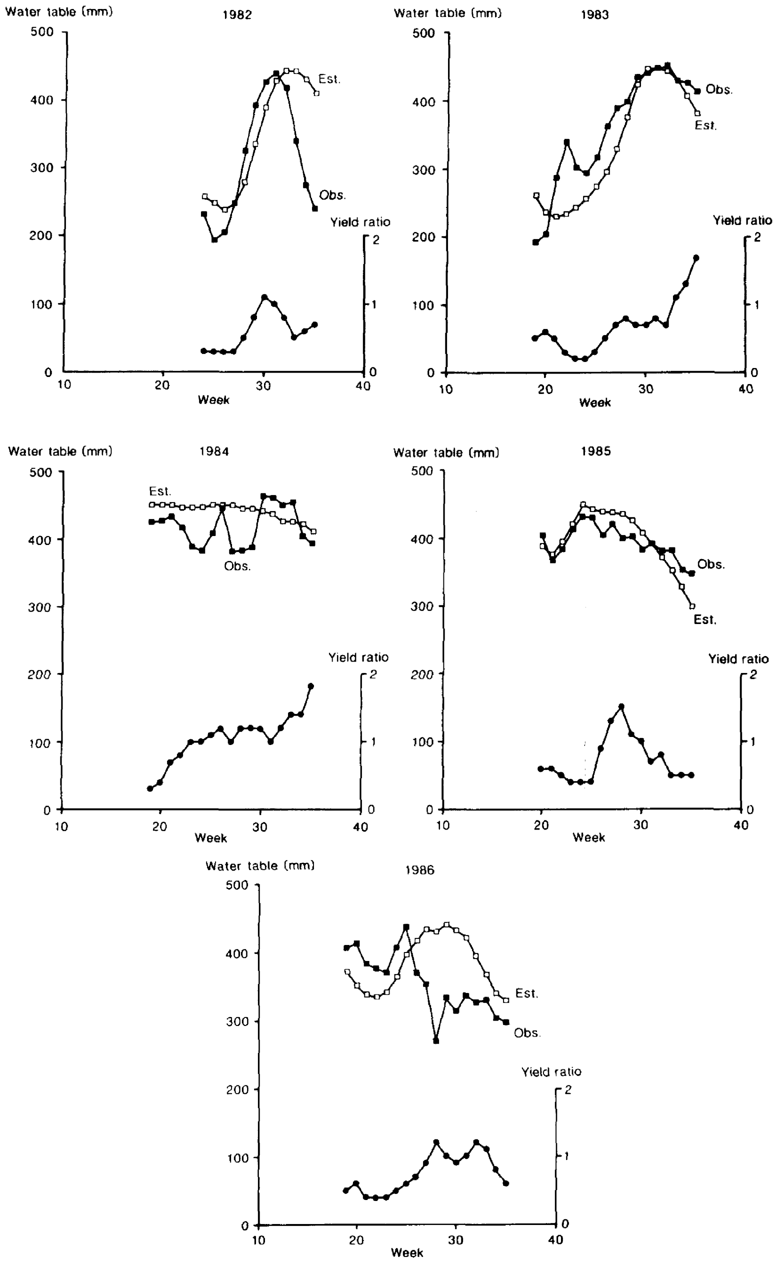

Fig. 1: Seasonal trends in yield ratio (●) and in measured (■) and calculated (□) water table depth (mm). Three-week running averages

TABLE 1: Summary of weather data

Year	Period weeks	Temperature °C	Rain mm d^{-1}	Sun hr d^{-1}	Evaporation mm d^{-1}
1982	21-26	14.3	2.5	5.2	2.7
1983	12-26	8.2	2.8	3.7	1.8
1984	12-26	9.8	1.7	5.1	2.0
1985	12-26	9.4	3.4	4.9	2.2
1986	12-26	8.7	3.6	4.7	2.1
1982	27-36	15.6	2.1	5.4	2.4
1983	27-44	14.1	2.8	3.9	1.5
1984	27-44	13.7	3.3	4.3	1.6
1985	27-44	12.9	4.1	3.1	1.5
1986	27-44	12.6	3.4	3.4	1.6
1982	21-36	15.1	2.2	5.3	2.5
1983	12-44	11.5	2.8	3.9	1.6
1984	12-44	11.9	2.6	4.7	1.7
1985	12-44	11.3	3.8	3.9	1.8
1986	12-44	10.8	3.5	4.0	1.8

duller compared to 1983 and 1984. Differences in rainfall occurred throughout the growing season. Differences in temperature and radiation occurred only in the second half of the season. Because the data for 1982 refer only to a short period of the season it is not included in the comparison.

The differences in herbage growth rate between reseed treatments (ignoring year of reseed) were generally small (Table 2). A significant effect was detected only in 1984 in the period before week 27 — growth rate was greatest for the newest reseed and least for the old sward. Herbage growth rate differences between

TABLE 2: Summary of herbage growth data (DM kg ha^{-1} d^{-1}). Brackets denote reseed treatment of current year

Year	Period weeks	Sward 1	Sward 2	Sward 3	Sward 4	Model
1982	21-26	19.4	(10.0)	(13.0)	(13.3)	85.7
1983	12-26	18.3	17.4	(12.2)	17.1	43.8
1984	12-26	28.7	38.4	46.6	(25.1)	61.4
1985	12-26	30.6	(—)	27.8	28.6	56.9
1986	12-26	23.9	19.6	(—)	25.0	46.5
1982	27-36	35.9	(29.7)	(31.3)	(35.7)	45.3
1983	27-44	32.1	31.1	(35.4)	32.1	31.9
1984	27-44	36.1	38.0	39.1	(47.6)	31.5
1985	27-44	23.8	(11.9)	21.9	22.3	25.4
1986	27-44	26.7	20.6	(17.4)	23.1	24.9
1982	21-36	29.2	(22.4)	(24.4)	(27.3)	60.5
1983	12-44	25.9	25.0	(19.3)	25.6	37.3
1984	12-44	32.9	38.1	42.6	(37.3)	45.1
1985	12-44	26.9	(6.4)	24.6	25.1	39.7
1986	12-44	25.4	20.1	(9.4)	24.0	34.7

The coefficient of variation of plot yield was approximately 0.23

years reflected the differences in weather. In the period before week 27 growth rates were greater in 1984 and 1985 compared to 1983 and 1986 — reflecting the higher temperature and radiation levels of the former two years. In the period after week 26 growth rates were least in 1985 and 1986, the years in which temperature and radiation levels were lowest.

Measured growth compared with model standard

Measured growth on the poorly-drained Ballinamore soil was less than would be expected in a well-drained soil (i.e. less than model estimates) particularly in the earlier part of the season. Measured herbage growth rates were close to the model estimates in the period after week 26 but in the earlier period measured rates were approximately 0.5 of the model estimates. For the period between week 12 and 44 as a whole measured growth rates were 0.32, 0.16, 0.36 and 0.33 of the model estimates in 1983, 1984, 1985 and 1986. These fractions showed a general correlation with rainfall, the fraction being least in years of greatest rainfall. The studies of Mulqueen (1985) indicated that herbage production on the undrained soil at Ballinamore was not depressed by drought in dry seasons. In the calculation of yield expected under well-drained conditions the model estimate for non-drought conditions was used.

Correlation of growth depression and water table

The week to week changes in the ratio of harvested yield (average of the reseed treatments, omitting current year reseed) and estimated yield are compared with the concurrent changes in the water table depth in Fig. 1. The form of the time curves for the yield ratio and water table depth were similar. In general the yield ratio was close to 1.0 when the water table depth exceeded 400 mm and was less than 1.0 otherwise. It is reasonable to assume that fluctuations in water table level will lead to corresponding fluctuations in the extent to which growth is affected by waterlogging. As the water table rises towards the soil surface a greater volume of soil will become water-saturated. Root respiration and microbial activity will lead to the depletion of soil O_2 and to the accumulation of CO_2. Reduced forms of mineral ions are produced which may be unavailable or toxic to the crop.

The initial depth to the water-table was relatively great in 1984, 1985 and 1986, indicating that the soil was not waterlogged. The low initial values of the yield ratio in these years may indicate that water saturation in winter has a residual effect and depresses pasture growth in the following spring. In the Netherlands, van Wijk and Feddes (1982) have related herbage growth restriction in spring to water table depth through the preceding winter months.

Water table model

The water table model successfully predicted the changes in the measured water table (Fig. 1) in all years but 1986. It is notable that in 1986 the yield ratio trend was more closely related to the modelled water table than to the observed trend.

Regression analysis (Table 3) showed that the yield ratio was 1.0 at 478 or 454 mm water table depth in the case of the measured or estimated depth. The ratio was generally more closely related to the water table depth calculated by the water table model than to the measured water table. This may be a reflection of the fact that the measured water table is

TABLE 3: Regression of yield ratio (R) on water table depth (W), combined data of 5 years

$R = -0.0035 + 0.002097\ W$
$SE = 0.000566^{**}$, $r = 0.39$, W = Measured water table, mm
$R = -0.3643 + 0.002977\ W$
$SE = 0.000495^{**}$, $r = 0.56$, W = Model water table, mm

$^{**}p < 0.01$

subject to error due to short-term fluctuations.

Trafficability and water table

Trafficability on drumlin soils is greatly reduced when the water content of the surface soil is greater than 0.89 (gg^{-1} dry soil) (Mulqueen, 1971). A comparison of the time trends in soil moisture content (Fig. 2) and in water table depth (Fig. 1) show that the two parameters are closely correlated and that the critical moisture content for trafficability is approached when the water table depth is approximately 320 mm.

As expected, regression analysis showed the soil water content of surface soil (D, fraction) and water table depth (W, model estimate) were significantly related by:—

$$D = 1.5690 - 0.002144\ W \quad \text{..........Equation 14}$$

$$SE = 0.000112^{**},\ r = 0.48$$

Within this overall relationship the soil moisture content tended to be higher than expected in 1985 and 1986 compared to the other years. This resulted in a relatively poor overall correlation when the five years were combined. The relatively higher soil moisture content in 1985 and 1986 may have been caused by rainfall contamination of the samples during collection. The frequency of rain days in these years was very high.

Discussion

Yield and stocking rate potential

In the 5 years of the experiment weather conditions varied widely — from an extremely dry, warm and bright year (1984) to an extremely wet, cool and dull year (1986). The estimated water table effects may be taken as providing an adequate indication of farming experience on the drumlin soils of the west of Ireland. The estimated reduction in herbage yield attributed to high water table effects ranged from 0.36 to 0.16 of the potential yield (excluding 1982) and the average reduction was 0.29. There is close agreement between this average value and the value used by the Netherlands Soil Survey Institute in the same type of soil (H.A.J. van Lannen, personal communication, 1988). These estimates also agree with earlier work at Ballinamore (Lee and Walsh, 1973; Mulqueen, 1985) and indicate clearly that the stocking rate potential of these soils is significantly reduced compared to well-drained soils. The reduction in stocking rate potential will be greater than 0.29 because the herbage output potential will be further decreased by the effect of poaching.

Seasonal pattern of growth and trafficability

The present analysis also confirms the observation of Mulqueen (1985) that the yield reduction due to high water table occurs mainly in spring and early summer and that reductions occurring later in the season are less. The data in Table 2 show that yield reductions in the period up to week 26 ranged from 0.59 to 0.38 and averaged 0.51. This halving of herbage

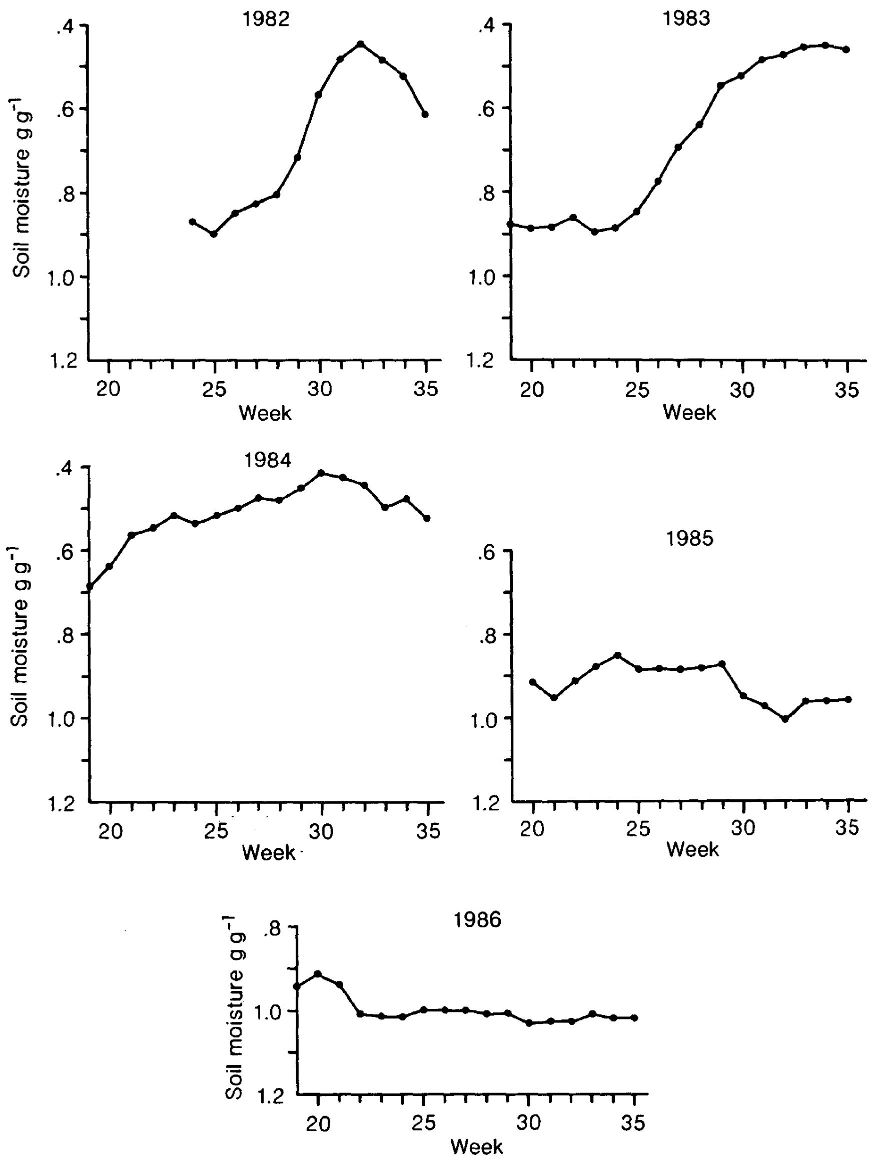

Fig. 2: Seasonal trends in soil moisture content. Three-week running averages. Sample depth 0-127 mm

production in the first part of the season has major implications for sward management.

Yield reductions were recorded in all years at the beginning of the season and at the end of the season in three years (1982, 1985, 1986). These reductions were of the order of 0.50 of potential yield. These yield reductions in spring and late autumn indicate that the potential duration of the grazing season in many years is less than 6 months.

The effect of water table depth on herbage production is relatively more important than its effect on trafficability. The soil becomes trafficable when the water table depth is greater than approximately 320 mm but the restriction of herbage production persists until the water table depth reaches approximately 450 mm. Nevertheless, the actual duration of the grazing season will be determined by the trends in soil moisture content. There was only one year during the experiment, i.e., 1984, when there was no poaching risk (Fig. 2). In two years (1982 and 1983) the poaching risk existed until late June or mid-July and in the remaining 2 years the risk was high throughout the season.

Grassland management on wet soils

The efficiency of a grass-based animal production system depends on the efficiency of herbage production and on the efficiency of utilisation of the herbage. Efficient utilisation depends on the seasonal adjustment of the areas allocated to grazing or silage in line with seasonal changes in herbage growth. In normal practice on well-drained soils, the grazing season begins during April and then approximately 0.50 of the farm area is closed for first cut silage. After the first silage cut, approximately 0.25 of the farm is closed for silage until late July when the second silage cut takes place. Subsequently all of the farm is grazed until late October.

The effects of water table on herbage production and soil trafficability at Ballinamore create major problems in the achievement of overall system efficiency. The year-to-year variation in the periods when the soil is trafficable and when herbage growth is unrestricted indicate that efficiency at Ballinamore will depend on the development of a flexible system of grassland management. The grazing season varied in duration from perhaps 5 months in 1984 to zero months in 1985 and 1986. In the three years when grazing was possible, the date of commencement of grazing varied from May to July.

Because of these extreme inter-year variations it is clear that there must be considerable flexibility in the amounts of herbage harvested mechanically, either as silage or as zero grazed grass. The development of appropriate machinery to do this is clearly of the greatest importance.

Farm production systems operate conventionally in a relatively rigid management framework because the factors controlling the system are relatively constant and predictable. At Ballinamore this is clearly not the case and it is important, therefore, that the producer should be able to monitor the condition of his system continuously so that he can alter his management strategy to suit. This analysis indicates that the key parameter at Ballinamore is the depth of the water table. The water table model is simple and suitable for on-farm use assuming appropriate soil information (classification, hydrology) is to hand. With appropriate weather forecasts it may be used to anticipate changes in water table depths.

The data presented indicates that "spot" readings of water table depth by prevailing techniques are less useful as a guide to growth and trafficability than the estimates of the water table model.

Acknowledgement

Mr. Ben Kilkenny, at Ballinamore, was responsible for tending the experiments, for recording and preliminary processing of the data. The authors are grateful to him for his dedicated commitment to the work.

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Received December 14, 1987

APPENDIX (abstract from Walsh, 1973)

The gley soils of the Ballinamore series

The parent material consists of a sticky glacial till derived from carboniferous limestone and shaley limestone with some sandstone influence.

The soils are poorly drained, of clay loam to clay texture and of medium base status. In the north of the county they tend to have coarser or "lighter" surface textures and a slightly higher sand content throughout the profile. This is due to metamorphic rock (mainly gneiss) influence in the Benbo mountain region and to an arenaceous limestone influence in the Kinlough-Lough Melvin area. The profile consists of a weakly structured A horizon, 5 to 15 cm thick, overlying a generally massive, sticky and plastic B horizon which varies from 30 to 40 cm in thickness. The A horizon has from 12 to 18% organic matter and an average of over 20% clay and 31% silt. However, the clay and silt contents vary widely from 11% clay and 21% silt in the extreme north to 36% clay and 46% silt near Ballinamore in the south. The B horizon which is much less variable in texture than the A horizon shows a significantly higher clay content throughout which ranges from 38 to 47%. This high clay content decreases in the C material. Large fragments of alder roots were found between 75 and 100 cm depth in most of the soil profile pits.