Irish Geography, 2013
Vol. 46, No. 3, 175–201, http://dx.doi.org/10.1080/00750778.2013.865364

Relationships between meteorological data and grass growth over time in the south of Ireland

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(*Received 23 April 2012; final version received 8 August 2013*)

Ireland has conditions that favour grass growth throughout most of the year, resulting in a competitive advantage in providing ruminant production systems with a cheap feed source. Grass growth is highly seasonal with little growth over the winter period due to low temperatures and low levels of sunshine/solar radiation. Peak grass growth occurs in late spring and early summer, and growth in the late summer and autumn is restricted as temperature and solar radiation decrease. Meteorological conditions influence grass growth over the course of the growing season, as a result there are variations in grass growth within and between years, making grass budgeting at farm level challenging. Meteorological patterns were examined, factors having the greatest influence on grass growth were determined and start of grass growth was studied from 1982 to 2010 at Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork, Ireland. Statistically significant patterns over the studied period were found in all of the meteorological variables studied. As expected, temperature had a big influence on grass growth in all seasons; evapotranspiration also plays a key role. These results suggest that it may be possible to use meteorological data to predict grass growth to help farmers to anticipate and organise the grazing management to match feed supply and demand. The study suggests that there are significant patterns in climate in Ireland, and that it might have future consequences on the rate of grass growth and on farm grassland management.

Keywords: Ireland; climate change; grass growth modelling; meteorological patterns; start of grass growth; meteorological factors

Introduction

Ireland has conditions that favour grass growth throughout most of the year, providing a competitive advantage over much of mainland Europe in offering the opportunity to provide ruminant production systems with a cheap feed source (Finneran *et al*. 2010). Grazed grass is the cheapest source of feed for beef and milk production in Ireland (O'Kiely 1994, Dillon *et al*. 2005a, Finneran *et al*. 2010). Grass constitutes approximately 70% of the diet of lactating dairy cows in Ireland (Dillon *et al*. 2005b).

The climate in Ireland is a temperate humid climate with maritime characteristics which are due to the influence of the North Atlantic Drift (Rohan 1986, Keane and

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Sheridan 2004). Mean daily temperature (°C) in Ireland varies from about 4°C in January to 14–16°C in July and August. In Ireland, rainfall can exceed 2800 mm annually in the western hills and is generally approximately 800 mm along the east coast and 1000 mm inland (Keane and Sheridan 2004). Annual quantities of bright sunshine hours range from less than 1200 hours in the mountain areas of the southwest, west and north to over 1600 hours in the southeast (Keane 1986). There are many studies on climate trends in temperature (McElwain and Sweeney 2003, Butler *et al*. 2007, McElwain and Sweeney 2007), rainfall (Hoppe and Kiely 1999, Murphy and Washington 2001, Sheridan 2001, McElwain and Sweeney 2003, Butler *et al*. 2007), sunshine hours (Stanhill 1998, Pallé and Butler 2001, 2002, Butler *et al*. 2007) and solar radiation (Stanhill 1998, Black *et al*. 2006, Stanhill 2011) in Ireland. Changes to precipitation patterns are more spatially and seasonally variable than are temperature changes (McElwain and Sweeney 2007), and so a comparison of changes in trends of precipitation between sites would be more difficult than a comparison of air temperatures. In Ireland, the occurrence of wet and dry winters has increased in the period 1951–2000 (Pauling and Paeth 2007). At a larger scale, there has been a small but increasing trend in precipitation annually and seasonally over land in the Northern Hemisphere during the twentieth century (Intergovernmental Panel on Climate Change [IPCC] 2001). The world global average surface temperature has experienced an increasing trend which is very likely slightly more than 0.65°C ± 0.2°C over the period from 1901 to 2005 (IPCC 2007).

In temperate regions, grass swards cover the ground almost completely, and light energy is received throughout the year. In reality there are marked seasonal variations in production. Grass growth is highly seasonal with little or no growth over the winter period due to low temperatures and low levels of sunshine/solar radiation. Peak grass growth occurs in late spring and early summer. In the late summer and autumn growth is restricted as temperature and solar radiation decrease (Brereton 1992). Grass growth rates can reach *circa* 100-kg dry matter (DM)/hectare (ha)/day in May when temperatures are greater than 10°C, but at similar temperatures later in the summer rates do not exceed 50-kg DM/ha/day (Brereton 1992). Due to variations in grass growth within and between years, feed budgeting at farm level is challenging.

Meteorological variables have an impact on grass growth; the most important that affect crop growth and development are radiation (Leafe *et al*. 1974), temperature (Aamlid *et al*. 2000) and rainfall (Burke *et al*. 2004). Light enables the transformation of CO_2 to biomass by the plant during photosynthesis (Leafe *et al*. 1974). During this process, photosynthetically active radiation is absorbed by chlorophyll and other pigments in the leaves of the plant and used for the reduction of CO_2 resulting in carbohydrates and oxygen (Burke *et al*. 2004). Temperature affects many physiological and growth functions of perennial ryegrass (*Lolium perenne* L.) including photosynthesis, respiration, spring growth, heading date and senescence. In temperate grasslands, the most important effect of temperature is on the length of the growing season (Hopkins 2000a). Grass growth will occur provided soil temperatures are not lower than 5°C and soil moisture is not limiting (Hopkins 2000b). Day length in Ireland varies from 10 hours in early spring to 16 hours in midsummer (Collins *et al*. 2004). Soil moisture is affected by the amount and distribution of rainfall, as well as by temperature and soil conditions (Hopkins 2000a). Soil moisture conditions have an impact on the length of the grazing season, grass growth rate and nutrient uptake and the loss of nutrients (Schulte *et al*. 2005). In Ireland, soil moisture is important, particularly during summer and in areas that experience seasonal drought (Hopkins 2000a). Evapotranspiration (ET) is the combination of the processes evaporation and transpiration (Collins *et al*. 2004). ET is affected by weather parameters, crop characteristics, management and environmental aspects. The magnitude of the water deficit and the soil type determine the effect of soil water content on ET. However, too much water can result in waterlogging which may limit root water uptake by inhibiting respiration (Allen *et al*. 1998). In Ireland, about 40% of the total incoming solar energy is used in evaporation/ET (Collins *et al*. 2004).

The objective of this study was to examine the patterns in meteorological data between 1982 and 2010 (maximum, minimum and mean air temperatures, soil temperatures, solar radiation, sunshine hours, rainfall and ET), to determine the factors having the greatest influence on grass growth and to study the start of grass growth over a 29-year period (from 1982 to 2010) at the Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork, Ireland (hereafter referred to as Moorepark).

Materials and methods

A range of meteorological and grass growth data was sourced at Moorepark, (latitude 50°07′ North, 8°16′ West) and compiled into a database. The data were set up into a number of different time steps: annual, monthly and season over the 29 years studied from 1982 to 2010. For the seasons, the data were divided into four seasons. Season one comprises months January to March, when grass is in the vegetative state. The main grass growing season is divided into two periods, season two and season three. Season two is April to mid-June, when grass becomes reproductive and peak grass growth occurs. Season three corresponds to the mid-June to August period when grass becomes vegetative again and growth declines. Season four is September to December, corresponding to autumn and winter when grass growth is in decline.

Meteorological data

Daily meteorological data are available from Moorepark for the years 1982 to 2010. The meteorological data available include rainfall (mm), minimum, maximum and mean air temperatures (°C), soil temperatures (°C), solar radiation (MJ/m^2/day) and sunshine hours (h). The data were collected at a meteorological station established at Moorepark by Met Éireann. Data were manually recorded from 1982 to 2005 inclusively, and data were electronically recorded thereafter. ET and day length were calculated.

When solar radiation data were not available from the meteorological station, data were calculated from the sunshine hours using the method described by Smith (1967). Likewise, the same method was used when solar radiation was available and sunshine hours were not. Day duration was calculated based on day of year according to the latitude in Ireland. ET was calculated (Equation 1) using the Hargreaves's formula (Stefano and Ferro 1997, Allen *et al*. 1998):

$$\mathrm{ET(mm)} = \mathrm{GEX}/247 \times (\mathrm{MeanT} + 17.8) \times (\mathrm{MaxT} - \mathrm{MinT})^{0,5} \times (0.0023) \qquad (1)$$

where, GEX: radiance of Earth, MeanT: mean daily air temperature (°C), MaxT: maximum daily air temperature (°C), MinT: minimum daily air temperature (°C) and 247: latent heat of vaporisation (=247 MJ/kg).

The other parameters (17.8 and 0.0023) were obtained by fitting ET_0 values to the Food and Agriculture Organization of the United Nations (FAO) Penman–Monteith method.

Trends and variability in meteorological data

The moving averages method was used to determine patterns in the meteorological data. This is a commonly used method for identifying patterns and has been used in the past to examine meteorological patterns (Hoppe and Kiely 1999, Kiely 1999, McElwain and Sweeney 2003, Black *et al*. 2006). This method calculates a set of averages, each one corresponding to a trend (*t*) (or pattern) value for a time point of the series. Each average is calculated by moving from one overlapping set of values to the next and is referred to as a moving average. In this study, a five-year moving average was used with the number of values in each set being five.

Ordinary least square regressions, with time as the sole explanatory variable, were fitted to the annual and monthly meteorological data. The statistical significance of the slopes of these lines was used to determine the presence of changes in patterns.

In order to capture the variability in the series the Pearson's coefficient of variation (CV) was calculated as the standard deviation divided by the mean and expressed as a percentage (Sweeney *et al*. 2008, Chapman *et al*. 2009). The CV is non-dimensional, therefore it can be used to compare variables with different units.

Grass growth data

Grass growth rates (kg DM/ha (hectare)/day) were measured at Moorepark from 1982 to 2010 using plots that were cut every four weeks. The same management was continuously applied to the grass growth plots over this period. The perennial ryegrass cultivars used in the plots changed every 5–10 years. Grass growth was measured using the methodology described by Corral and Fenlon (1978). This methodology estimates grass growth on a four-week harvest interval. Four series of plots are harvested in rotation, spaced one week apart and herbage mass is recorded at each harvest. A simple quadratic function (Equation 2) is used to represent grass growth rate accelerating steadily from zero immediately after harvest. The data are used to construct growth curves showing the rate at which DM is produced each week (kg DM/ha/week) of the growing season, on swards which are being harvested monthly. The quadratic equation for growth rate in week t is:

$$\text{Rate}_t = (A_1 Y_t + A_2 Y_{t-1} + A_3 Y_{t-2} + A_4 Y_{t-3})/28 \tag{2}$$

where, Y_t, Y_{t-1}, Y_{t-2} and Y_{t-3} are the harvested yields at the ends of weeks t, t-1, t-2 and t-3, respectively, and A_1 = 7/16, A_2 = 5/16, A_3 = 3/16 and A_4 = 1/16, with greater weight given to plots nearer harvest.

Weekly growth is divided by seven to give average daily grass growth in kg DM/ha/day.

Start of grass growth

As previously stated, temperature is one of the main factors influencing grass growth. To identify when the grass growing season commences in each year, the start of grass growth was defined as the first day in which 10-kg DM/ha/day were grown. Daily soil temperature (°C) at 50 mm and daily mean air temperature were accumulated from 1 January until the day in which 10-kg DM/ha/day were grown. An average of these accumulated soil temperatures and mean air temperatures were calculated over the 28 years. The days, dates and variation of the start of grass growth between years were recorded.

Relationship between meteorological and grass growth data

Statistical analysis

The moving averages were calculated in Microsoft Excel. The statistical package Predictive Analytics SoftWare (PASW) statistics for Windows by Statistical Package for Social Sciences (SPSS): Version 18.0 (SPSS Inc. 2009) was used to calculate the correlations between all available meteorological variables and grass growth, and to run the regression analysis of the meteorological variables where grass growth was included as the dependent variable. Day length was removed from the analysis as although it varies throughout the year, it does not vary between years at a given latitude, and when included in the analysis it masked the other meteorological factors that are variable between years. Correlation analysis was performed to identify the variables which were highly associated with each other and with grass growth. As there were a large number of candidate variables, forward stepwise linear regression models were developed to select the statistically significant variables to construct the final model (significance at the 5% level) with the non-significant explanatory variables removed. In the models, grass growth was the dependent variable and independent variables included were mean, minimum and maximum air temperatures, sunshine hours, soil temperatures at 50 mm and 100 mm, rainfall, solar radiation and ET. Separate regression models were used for each season. As ET was a calculated variable, to see the effect of ET on grass growth two regression analyses were conducted for each season, the first without ET, and the second with ET as an explanatory variable. Correlation amongst predictor variables in the regression analysis is referred to as multicollinearity, and can result in very imprecise regression coefficients that are difficult to interpret. To examine if multicollinearity occurred in this study, the tolerance and the variance inflation factor (VIF) of the variables included in the model were also calculated in SPSS (SPSS Inc. 2009). There is no formal criterion for determining the bottom line of the tolerance value or VIF. In this study, VIF greater than 10 were considered high and excluded from the model.

Daily meteorological data were converted to weekly average data as grass growth measurement was weekly. All meteorological variables had 1508 observations (29 years by 52 weeks), and there were 1078 grass growth observations as grass growth measurements commenced in late February/March and finished in late October/November. There was no grass growth data available for the year 1996 (therefore, there were 28-years grass growth data). The meteorological data were divided into four seasons, as described above: the first from January to March (377 observations), the second from April to mid-June (319 observations), the third from mid-June to August (319 observations) and the fourth season from September to December (493 observations). Dividing the grass growth data into seasons resulted in the first season having 188 observations, the second had 308 observations, the third had 308 observations and the fourth had 274 observations.

Results

Meteorological data

Air temperature

January had the greatest variability, as measured by the CV, for maximum (CV = 16%), minimum (CV = 80%) and mean (CV = 26%) air temperatures (Table 1). Mean

Table 1. Summary of the monthly mean of the meteorological variables (average maximum, minimum and mean temperature, total rainfall, total sunshine, total solar radiation and average soil temperature at 50 mm and at 100 mm) over the period 1982–2010 and the coefficient of variation (CV) expressed as a percentage in brackets.

	MaxT (°C)	MinT (°C)	MeanT (°C)	Rain (mm)	Sun (h)	SolRad (MJ/m^2)	SoilT 50 (°C)	SoilT 100 (°C)	ET (mm)
January	8.7 (16%)	2 (80%)	5.3 (26%)	111.2 (44%)	44.3 (29%)	79.43 (10%)	4.9 (27%)	5.1 (25%)	15.1 (9%)
February	8.9 (16%)	2.2 (61%)	5.6 (23%)	78.9 (62%)	63.3 (23%)	126.31 (10%)	5.1 (26%)	5.2 (25%)	22.5 (11%)
March	10.7 (9%)	3.1 (38%)	6.9 (14%)	82.5 (39%)	97.6 (29%)	228.22 (13%)	6.9 (14%)	6.7 (15%)	43.4 (7%)
April	12.77 (10%)	4 (30%)	8.4 (14%)	67.0 (45%)	150.0 (21%)	355.09 (11%)	9.4 (13%)	8.9 (14%)	66.9 (7%)
May	15.6 (8%)	6.4 (17%)	11.0 (9%)	64.9 (52%)	183.1 (21%)	461.86 (12%)	13.0 (8%)	12.3 (9%)	95.1 (8%)
June	18.1 (6%)	9.4 (9%)	13.8 (6%)	70.8 (49%)	155.2 (31%)	439.86 (17%)	16.1 (8%)	15.3 (9%)	106.4 (7%)
July	19.8 (7%)	11.4 (7%)	15.6 (6%)	64.9 (58%)	152.2 (28%)	430.91 (14%)	17.5 (6%)	16.8 (6%)	110 (10%)
August	19.6 (8%)	11.0 (10%)	15.3 (8%)	85.7 (67%)	150.4 (22%)	377.18 (11%)	16.8 (6%)	16.3 (7%)	93.8 (9%)
September	17.4 (5%)	8.9 (15%)	13.1 (7%)	75.7 (57%)	120.7 (20%)	265.41 (10%)	14.2 (7%)	13.9 (8%)	64.3 (7%)
October	14.1 (8%)	6.6 (24%)	10.3 (12%)	113.5 (42%)	83.9 (23%)	162.38 (10%)	10.9 (12%)	10.9 (12%)	37.4 (6%)
November	10.9 (9%)	4.0 (33%)	7.4 (14%)	104.5 (54%)	57.8 (25%)	89.77 (10%)	7.7 (15%)	7.8 (15%)	19 (9%)
December	9.1 (16%)	2.6 (68%)	5.9 (26%)	100.8 (39%)	38.8 (28%)	62.15 (9%)	5.8 (22%)	6.0 (21%)	12. 6 (8%)

Table 2. Summary of annual and monthly meteorological patterns (mean temperature, maximum temperature, minimum temperature, rainfall, sunshine hours, soil temperature at 50 mm) from 1982 to 2010 at Moorepark. Monthly patterns of solar radiation and soil temperature at 100 mm are shown in Figures 1 and 2, respectively.

Variable	Period	Trendline	R^2	P value
Mean temperature	Annual	$y = 0.016x + 9.7$	0.07	0.16
	January	$y = 0.020x + 5.03$	0.01	0.53
	February	$y = 0.010x + 5.4$	0.005	0.73
	March	$y = 0.010x + 6.7$	0.01	0.66
	April	$y = 0.048x + 7.6$	0.13	0.06
	May	$y = 0.042x + 10.4$	0.13	0.06
	June	$y = 0.041x + 13.2$	0.17	0.03*
	July	$y = -0.024x + 16.0$	0.04	0.28
	August	$y = 0.011x + 15.1$	0.01	0.69
	September	$y = 0.032x + 12.6$	0.08	0.14
	October	$y = 0.027x + 9.9$	0.03	0.38
	November	$y = 0.029x + 7.0$	0.05	0.22
	December	$y = -0.053x + 6.7$	0.09	0.12
Maximum temperature	Annual	$y = 0.018x + 13.6$	0.09	0.11
	January	$y = 0.019x + 8.4$	0.01	0.53
	February	$y = 0.038x + 8.4$	0.05	0.27
	March	$y = 0.029x + 10.2$	0.06	0.19
	April	$y = 0.046x + 12.1$	0.10	0.10
	May	$y = 0.039x + 15.0$	0.08	0.16
	June	$y = 0.052x + 17.4$	0.15	0.05*
	July	$y = -0.043x + 20.5$	0.07	0.19
	August	$y = 0.002x + 19.5$	0.0001	0.94
	September	$y = 0.039x + 17.0$	0.14	0.05*
	October	$y = 0.040x + 13.5$	0.09	0.11
	November	$y = 0.032x + 10.4$	0.08	0.13
	December	$y = -0.065x + 10.1$	0.15	0.04*
Minimum temperature	Annual	$y = 0.014x + 5.8$	0.049	0.25
	January	$y = 0.024x + 1.6$	0.02	0.50
	February	$y = -0.016x + 2.4$	0.01	0.60
	March	$y = -0.008x + 3.2$	0.003	0.75
	April	$y = 0.049x + 3.2$	0.12	0.06
	May	$y = 0.045x + 5.7$	0.12	0.06
	June	$y = 0.033x + 9.0$	0.12	0.07
	July	$y = -0.001x + 11.4$	0.0001	0.96
	August	$y = 0.019x + 11.0$	0.02	0.46
	September	$y = 0.028x + 8.4$	0.03	0.35
	October	$y = 0.012x + 6.4$	0.0041	0.74
	November	$y = 0.026x + 3.6$	0.03	0.37
	December	$y = -0.043x + 3.3$	0.04	0.29
Rainfall	Annual	$y = -0.964x + 1035.1$	0.005	0.72
	January	$y = 0.142x + 109.1$	0.0006	0.90
	February	$y = -1.482x + 101.1$	0.07	0.18
	March	$y = -0.334x + 87.5$	0.01	0.65
	April	$y = 0.147x + 64.8$	0.002	0.83
	May	$y = 0.304x + 60.4$	0.01	0.69
	June	$y = -0.855x + 83.7$	0.04	0.28
	July	$y = 2.133x + 33.0$	0.23	0.01**
	August	$y = -0.468x + 93.0$	0.005	0.72
	September	$y = 0.118x + 74.0$	0.0005	0.90
	October	$y = -0.184x + 116.3$	0.001	0.87
	November	$y = 0.899x + 91.0$	0.02	0.48
	December	$y = -1.384x + 121.6$	0.09	0.12

Table 2 (*Continued*)

Variable	Period	Trendline	R^2	P value
Sunshine hours	Annual	$y = 12.927x + 1103.4$	0.39	0.0003**
	January	$y = 0.466x + 37.3$	0.09	0.11
	February	$y = 0.655x + 53.5$	0.15	0.04*
	March	$y = 1.754x + 71.3$	0.28	0.003**
	April	$y = 1.531x + 127.1$	0.17	0.03*
	May	$y = 1.073x + 167$	0.06	0.22
	June	$y = 2.722x + 114.3$	0.23	0.01**
	July	$y = 0.584x + 143.4$	0.01	0.55
	August	$y = 1.423x + 129.0$	0.14	0.05*
	September	$y = 0.934x + 106.7$	0.11	0.08
	October	$y = 0.626x + 74.5$	0.08	0.14
	November	$y = 0.598\mathrm{x} + 48.8$	0.12	0.06
	December	$y = 0.561x + 30.4$	0.19	0.02*
Soil temperature at 50 mm	Annual	$y = 0.035x + 10.2$	0.2309	0.01**
	January	$y = 0.016x + 4.7$	0.01	0.60
	February	$y = 0.028x + 4.7$	0.03	0.37
	March	$y = 0.021x + 6.57$	0.03	0.35
	April	$y = 0.063x + 8.4$	0.20	0.01**
	May	$y = 0.058x + 12.2$	0.23	0.01**
	June	$y = 0.090x + 14.8$	0.38	0.0004**
	July	$y = 0.026x + 17.1$	0.04	0.28
	August	$y = 0.041x + 16.2$	0.11	0.08
	September	$y = 0.060x + 13.3$	0.28	0.003**
	October	$y = 0.043x + 10.2$	0.08	0.13
	November	$y = 0.022x + 7.4$	0.03	0.40
	December	$y = -0.048x + 6.5$	0.10	0.10
Solar radiation	Annual	$y = 15.662x + 2843.6$	0.40	0.0002**
Soil temperature at 100 mm	Annual	$y = 0.055x + 9.6$	0.44	0.00009**

Note: Significance: *$P < 0.05$, **$P < 0.01$. The P value refers to the statistical significance of the slopes of the least square regression lines.

temperature was most variable in December (CV = 26%), and maximum temperature was most variable in December and February (CV = 16%). The lowest variation in the minimum temperature occurred in July (CV = 7%) and in mean temperature in June and July (CV = 6%). September was the month with lowest variation in maximum temperature (CV = 5%); maximum temperature had the lowest CV of all the meteorological variables in 7 of the 12 months.

Mean air temperature showed a significant increasing trend in June ($P = 0.03$, Table 2). Maximum temperature showed a significantly increasing trend in June and September ($P = 0.05$) and a significantly decreasing trend in December ($P = 0.04$, Table 2). Minimum temperature experienced no significant patterns in any month (Table 2). The values of R^2 of all air temperatures were low in most cases (Table 2). Annual average mean, maximum and minimum air temperatures over the period 1982–2010 showed an increase of 0.5°C which was not statistically significant (Table 2).

Rainfall

Rainfall was the meteorological variable with the most variation. The greatest variation occurred in August (CV = 67%) and the least in March and December (CV = 39%; Table 1). There was a significant increase in July ($P < 0.01$, Table 1). The values of R^2 of rainfall were low in most cases (Table 2). Annual total rainfall showed a slight but not significant decrease over the whole period (Table 2).

Sunshine hours

Annual total sunshine hours measured at Moorepark showed a significant positive trend ($P < 0.001$, Table 2), increasing by approximately 400 sunshine hours over the period 1982–2010. Sunshine hours had a maximum CV in June (CV = 31%) and minimum in September (CV = 20%, Table 1). There were significant increases in sunshine hours in February, March, April, June, August and December ($P < 0.05$, Table 2). Annual sunshine had the greatest R^2 of all the meteorological variables studied at Moorepark (0.39, Table 2).

Solar radiation

Similar to sunshine hours, annual total solar radiation at Moorepark experienced a significant positive trend (Table 2). Variation in solar radiation was greatest in June (CV = 17%) and least in December (CV = 9%, Table 1). Total monthly solar radiation and its five-year moving average are shown in Figure 1. Significant increases ($P < 0.05$) were observed in March, April, June, August and September and the greatest R^2 in June (0.30, Figure 1).

Soil temperature

Both annual average soil temperature at 50 mm and annual average soil temperature at 100 mm showed significant increases (Table 2). Soil temperature at 50 mm had the highest CV in January (CV = 27%) and the lowest in July and August (CV = 6%), while soil temperature at 100 mm had the highest CV in January and February (CV = 25%) and the lowest in July (CV = 6%, Table 1). Soil temperature at 50 mm showed significant increases in April, May, June and September ($P < 0.05$; Table 2). Average monthly soil temperature at 100 mm and its five-year moving average are shown in Figure 2. Increasing patterns in soil temperature at 100 mm were significant in the months from April to September. Both soil temperatures had the highest R^2 in June (0.38, Table 2; 0.55, Figure 2).

Grass growth data

Box plots of grass growth measured at Moorepark over the period are shown per month in Figure 3a and per week of year in Figure 3b. There is large variability in grass growth within years (e.g. CV = 85% in 1989) and between years (there is a difference of 57% between the year with the greatest grass growth rate and the lowest); grass growth over the 28 years (inter annum CV = 14%) was greatest in 1997 (average 72-kg DM/ha/day), and least in 1982 (average 41-kg DM/ha/day).

In season one (January to March, CV = 70%), the year with the greatest grass growth rate was 1999 with an average daily grass growth rate of 60-kg DM/ha/day, and the lowest was 1986 with just 1-kg DM/ha/day. In season two (April to mid-June, CV = 12%), the greatest grass growth rate was observed in 1988 with 113-kg DM/ha/day on average, while the lowest was registered in 1993 with 64-kg DM/ha/day. In season three (mid-June to August, CV = 23%), 1988 had the greatest grass growth with average daily rates of 93-kg DM/ha/day and 1989 had the lowest with 34-kg DM/ha/day. In season four

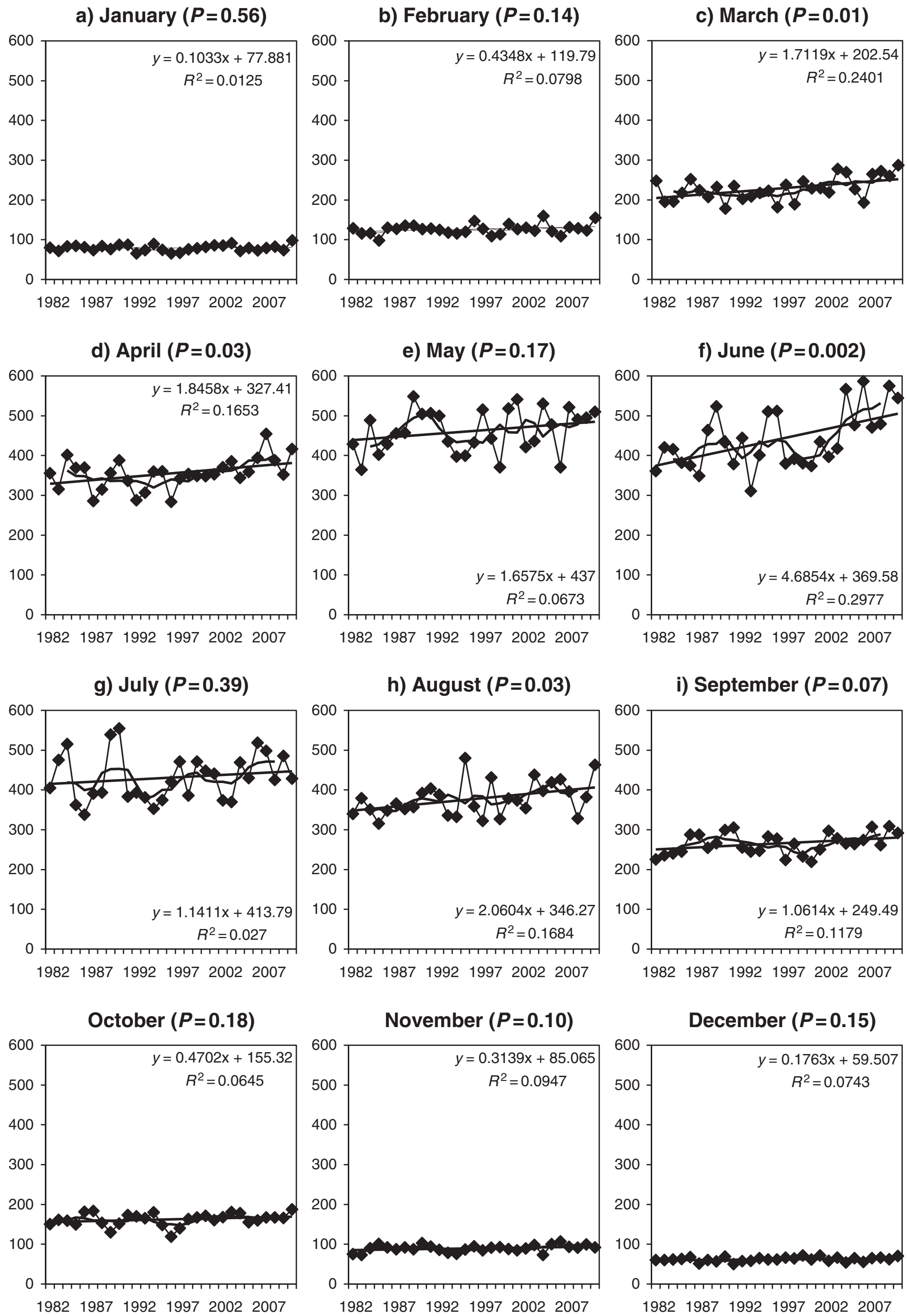

Figure 1. Total monthly solar radiation (MJ/m^2) from 1982 to 2010 for (a) January to (l) December and five-year moving average at Moorepark. *P* values refer to the hypotheses that the trend is significant.

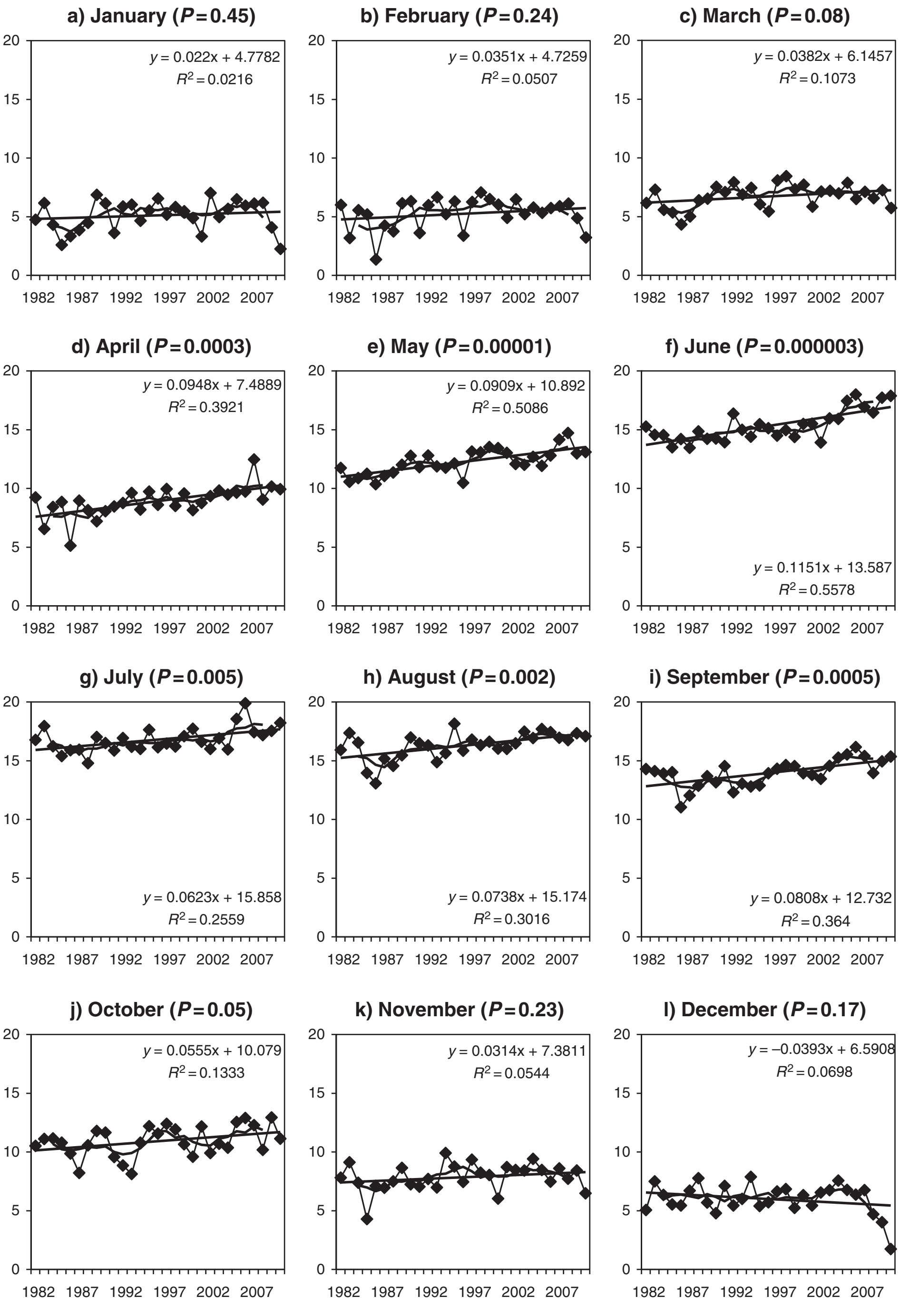

Figure 2. Monthly average soil temperature (°C) at 100 mm for (a) January to (l) December from 1982 to 2010 and five-year moving average at Moorepark. *P* values refer to the hypotheses that the trend is significant.

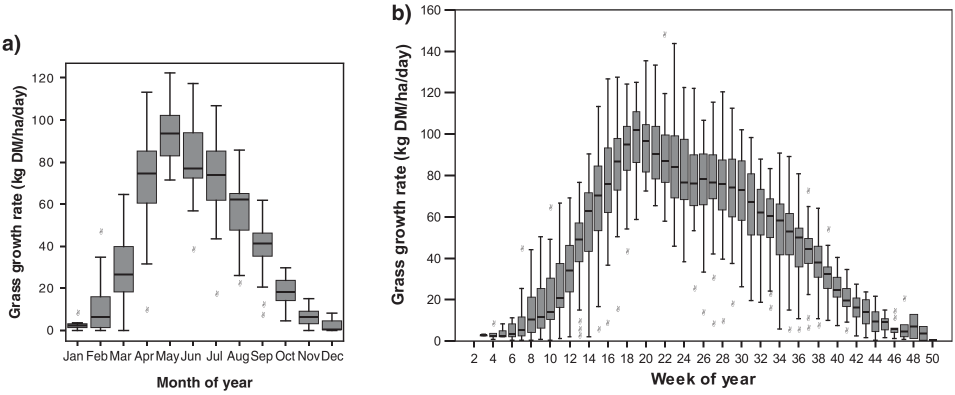

Figure 3. Boxplot of measured grass growth rate (kg DM/ha/day) at Moorepark over the period 1982 to 2010 (a) per month and (b) per week. Median line, minimum and maximum, outliers and extremes are displayed for each box. Outliers are between 1.5 box lengths and 3 box lengths from the end of the box. Extremes are more than three box lengths from the end of the box.

(September to December, CV = 31%), 2006 had the greatest grass growth rates with an average of 45-kg DM/ha/day and 1991 had the lowest with 9-kg DM/ha/day.

Start of grass growth season

The date on which grass growth measurements commenced varied between years, from week 3 in 2010 to week 13 in 1986. The mean accumulated soil temperatures from 1 January necessary to produce 10-kg DM/ha/day was 325°C accumulated thermal time on average for the 28 years (CV = 27%). The maximum soil accumulated temperature at which grass growth was 10-kg DM/ha/day or greater was 476.1°C in 1993, and the minimum mean accumulated soil temperature was 176.3°C in 1983. It took an average of 64 days from the 1 January for grass growth rates to reach 10-kg DM/ha/day or greater over the 28 years; the maximum number of days required was in 1986 with 113 days, and the minimum in 2008 with 36 days. The regression analysis of the start date of grass growth over time was not significant; however, the start of grass growth at Moorepark seems to be advancing as the five-year moving average showed a tendency to decrease, starting at 81.8 and finishing at 63.6 days. The average of the mean air temperature from 1 January required to produce 10-kg DM/ha/day was 351°C accumulated thermal time (CV = 26%), the maximum was 508.9°C in 1987 and the minimum 194.7°C in 1983. The total sunshine hours accumulated from 1 January until the start of grass growth were 127 hours on average (CV = 55%), the maximum was 354.2 hours in 1986 and the minimum 28 hours in 1992.

Relationship between meteorological and grass growth data

The relationship between grass growth and the meteorological variables in each season is graphically represented in Figures 4–7 with fitted linear or polynomial regression lines depending on the appropriateness. In season one (Figure 4), all of the meteorological variables had a positive relationship with grass growth except for rainfall. Air and soil temperatures followed a similar pattern in their relationship with grass growth; as temperature increased grass growth increased. ET also showed a positive relationship

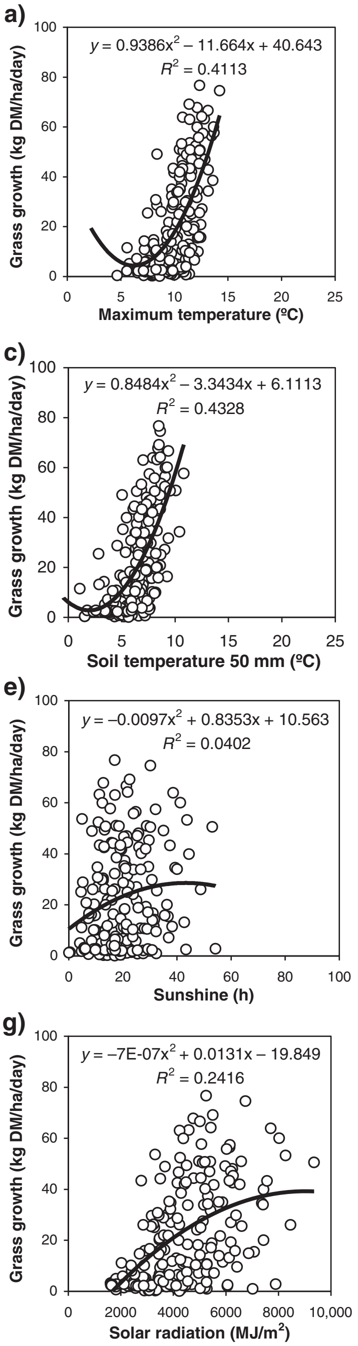

Figure 4. Relationship between grass growth and meteorological indicators (maximum and minimum temperature, soil temperature at 50 mm and 100 mm, sunshine, rainfall, solar radiation and evapotranspiration) at Moorepark in season one (January to March) over the period 1982 to 2010.

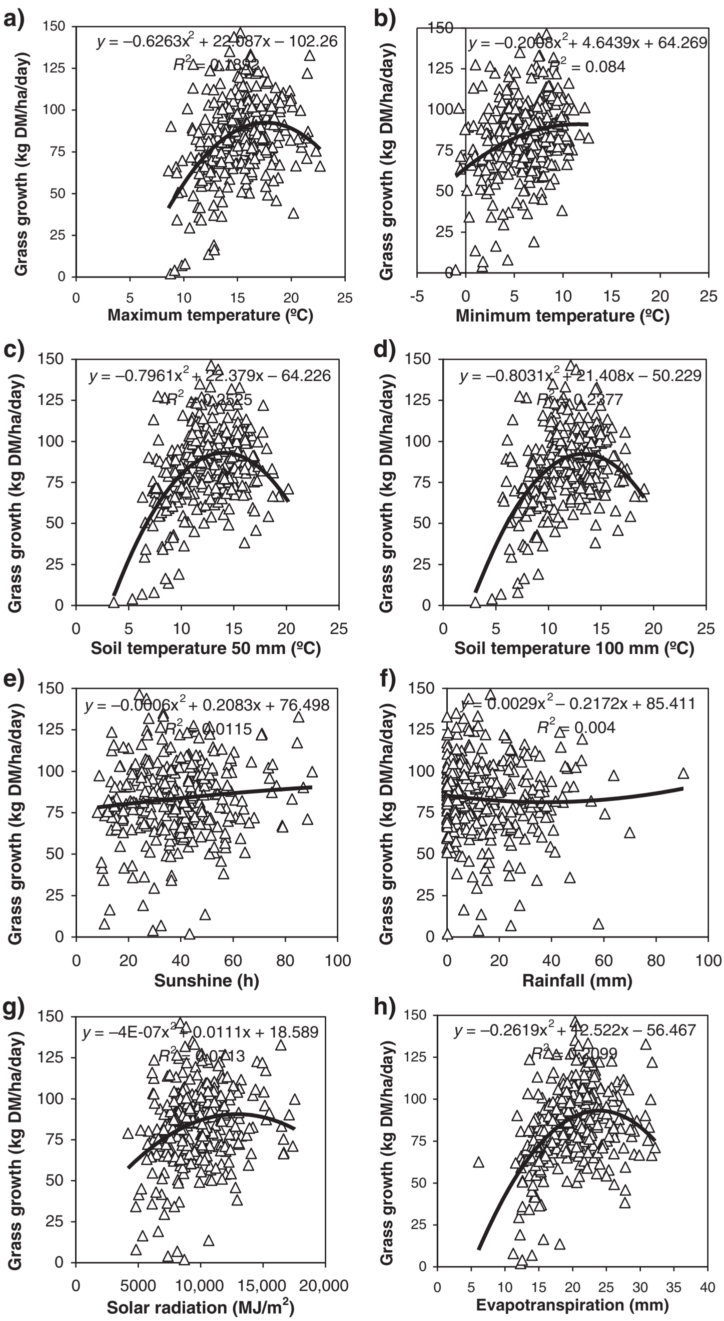

Figure 5. Relationship between grass growth and meteorological indicators (maximum and minimum temperature, soil temperature at 50 mm and 100 mm, sunshine, rainfall, solar radiation and evapotranspiration) at Moorepark in season two (April to mid-June) over the period 1982 to 2010.

with the largest correlation coefficient in season one. In season two (Figure 5), air and soil temperatures showed a similar pattern. Soil temperature at 50 mm had the strongest relationship with grass growth (R^2 = 0.2525). Sunshine hours, solar radiation and ET had a positive relationship, while rainfall had a negative relationship with grass growth. In season three (Figure 6), all air and soil temperatures had a negative relationship with grass growth, with maximum temperature having the greatest negative effect shown on the slope of the trendline (R^2 = 0.1436). The only variable with a positive relationship with grass growth was rainfall. In season four (Figure 7), all variables experienced a positive relationship with grass growth except rainfall. The slopes of all temperature trendlines were very similar. ET had the strongest relationship with grass growth (R^2 = 0.5703).

Correlation analysis

The correlation analysis results are shown in Table 3. As expected, air temperatures were correlated with soil temperatures in all seasons and solar radiation was with sunshine in all seasons (>0.800), ET was highly correlated with maximum temperature (>0.500) and solar radiation (>0.700), and both soil temperatures had the highest positive correlations in all the seasons (>0.900). The highest negative correlations were minimum temperature with rainfall in season one; sunshine with rainfall in seasons two and four; and grass growth with maximum temperature in season three.

Linear regression analysis

Linear regression analysis results are shown in Table 4. Taking into account all meteorological variables except ET, the meteorological factors having the greatest effect on grass growth at Moorepark in season one were soil temperature at 50 mm, solar radiation and rainfall; in season two it was soil temperature at 50 mm; in season three it was maximum temperature, solar radiation, sunshine hours and minimum temperature and in season four it was solar radiation and sunshine (Table 4a). The best fit of the model was in season four (adjusted R^2 = 0.612). Temperature and solar radiation had a big effect on grass growth in all seasons (Table 4a).

When considering the regression analysis with ET as an explanatory variable, the meteorological factors having the greatest effect on grass growth at Moorepark in season one were ET and soil temperature at 100 mm; in season two it was soil temperature at 50 mm; in season three it was maximum daily temperature, ET, minimum daily temperature and sunshine hours; and in season four it was ET and minimum daily temperature (Table 4b). Seasons one and four had the best fit with higher adjusted R^2 (adjusted R^2 > 0.500). In seasons two and three, the adjusted R^2 were of 0.121 and 0.326, respectively. Temperature had a big influence on grass growth in all seasons. For three of the four seasons, the main important factor was ET (Table 4b). The meteorological factor with a big influence on grass growth in season two was soil temperature at 50 mm whether ET is included as an explanatory variable or not.

Discussion

Meteorological data

An index of atmospheric circulation normally cited in studies on Northern European climate variability is the North Atlantic Oscillation (NAO) which makes the detection of a

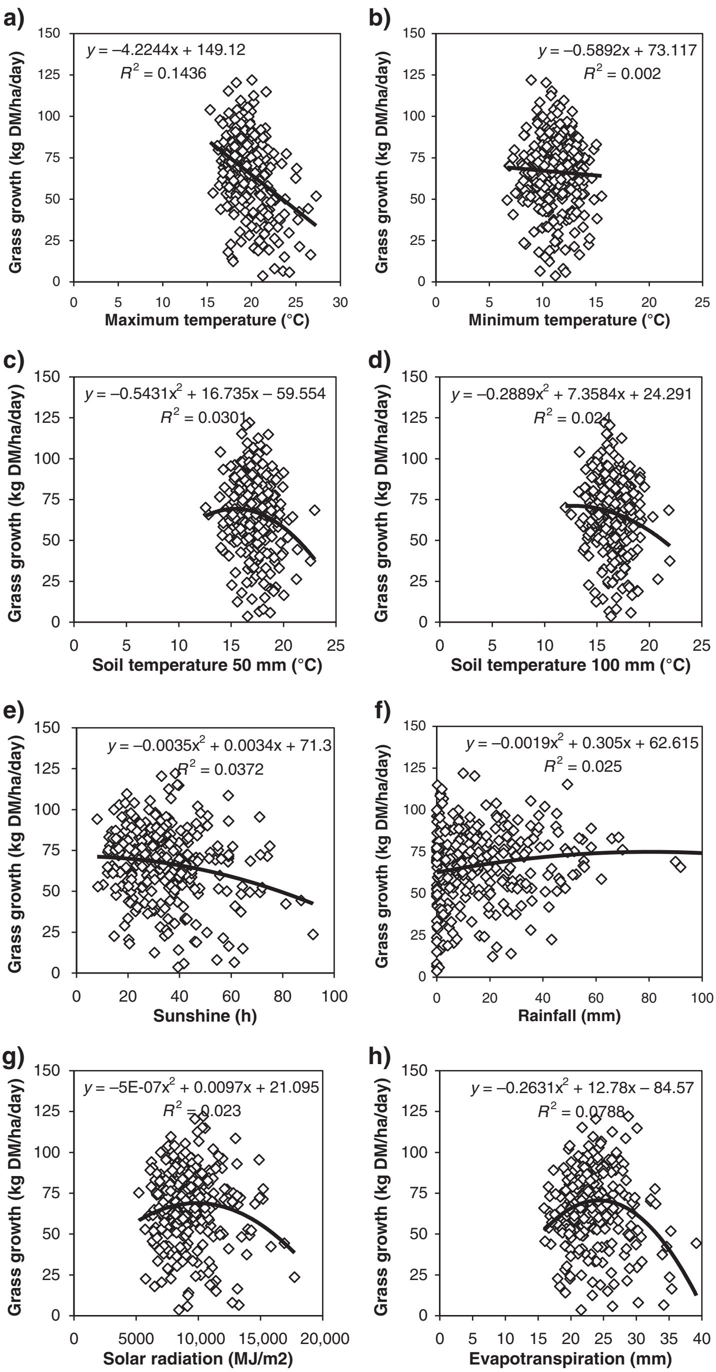

Figure 6. Relationship between grass growth and meteorological indicators (maximum and minimum temperature, soil temperature at 50 mm and 100 mm, sunshine, rainfall, solar radiation and evapotranspiration) at Moorepark in season three (mid-June to August) over the period 1982 to 2010.

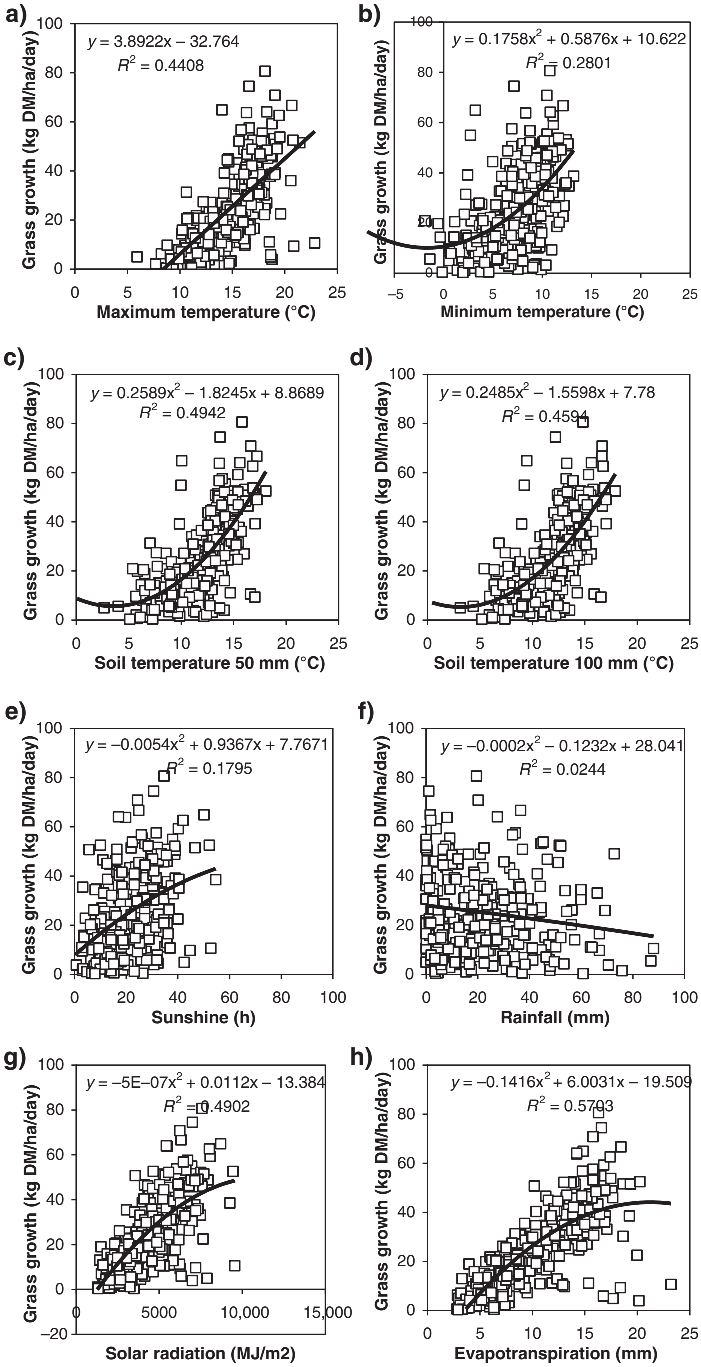

Figure 7. Relationship between grass growth and meteorological indicators (maximum and minimum temperature, soil temperature at 50 mm and 100 mm, sunshine, rainfall, solar radiation and evapotranspiration) at Moorepark in season four (September to December) over the period 1982 to 2010.

Table 3. Correlation matrix of weekly meteorological variables and weekly grass growth per season (S1–S4 correspond to seasons 1–4, respectively).

		MaxT	MinT	Sun	Rain	SoilT50	SoilT100	SolRad	ET	GrassGro
MaxT	S 1	1	0.759**	0.113*	0.112*	0.883**	0.874**	0.340**	0.560**	0.609**
	S 2	1	0.706**	0.417**	−0.243**	0.900**	0.897**	0.636**	0.920**	0.342**
	S 3	1	0.442**	0.524**	−0.371**	0.748**	0.677**	0.488**	0.695**	−0.379**
	S 4	1	0.867**	0.559**	−0.021	0.957**	0.954**	0.801**	0.885**	0.664**
MinT	S 1	0.759**	1	−0.293**	0.133**	0.862**	0.863**	0.007	0.225**	0.433**
	S 2	0.706**	1	−0.148**	0.132*	0.779**	0.822**	0.107	0.492**	0.279**
	S 3	0.442**	1	−0.234**	−0.007	0.537**	0.611**	−0.195**	−0.032	−0.045
	S 4	0.867**	1	0.240**	0.052	0.911**	0.911**	0.551**	0.649**	0.516**
Sun	S 1	0.113*	−0.293**	1	−0.173**	−0.009	−0.030	0.856**	0.610**	0.188**
	S 2	0.417**	−0.148**	1	−0.406**	0.279**	0.236**	0.922**	0.524**	0.107
	S 3	0.524**	−0.234**	1	−0.298**	0.395**	0.316**	0.916**	0.593**	−0.186**
	S 4	0.559**	0.240**	1	−0.221**	0.504**	0.498**	0.887**	0.751**	0.421**
Rain	S 1	0.112*	0.133**	−0.173**	1	0.073	0.069	−0.170**	−0.126*	−0.116
	S 2	−0.243**	0.132*	−0.406**	1	−0.098	−0.076	−0.376**	−0.288**	−0.046
	S 3	−0.371**	−0.007	−0.298**	1	−0.269**	−0.189**	−0.290**	−0.370**	0.151**
	S 4	−0.021**	0.052	−0.221	1	−0.029	−0.028	−0.188**	−0.148**	−0.156**
SoilT50	S 1	0.883**	0.862**	−0.009	0.073	1	0.990**	0.311**	0.532**	0.629**
	S 2	0.900**	0.779**	0.279**	−0.098	1	0.979**	0.539**	0.858**	0.352**
	S 3	0.748**	0.537**	0.395**	−0.269**	1	0.923**	0.443**	0.577**	−0.145*
	S 4	0.957**	0.911**	0.504**	−0.029	1	0.997**	0.785**	0.863**	0.685**
SoilT100	S 1	0.874**	0.863**	−0.030	0.069	0.990**	1	0.267**	0.483**	0.624**
	S 2	0.897**	0.822**	0.236**	−0.076	0.979**	1	0.499**	0.824**	0.336**
	S 3	0.677**	0.611**	0.316**	−0.189**	0.923**	1	0.355**	0.423**	−0.148**
	S 4	0.954**	0.911**	0.498**	−0.028	0.997**	1	0.775**	0.853**	0.663**
SolRad	S 1	0.340**	0.007	0.856**	−0.170**	0.311**	0.267**	1	0.909**	0.478**
	S 2	0.636**	0.107	0.922**	−0.376**	0.539**	0.499**	1	0.754**	0.213**
	S 3	0.488**	−0.195**	0.916**	−0.290**	0.443**	0.355**	1	0.747**	−0.041
	S 4	0.801**	0.551**	0.887**	−0.188**	0.785**	0.775**	1	0.958**	0.692**

Table 3 (*Continued*)

		MaxT	MinT	Sun	Rain	SoilT50	SoilT100	SolRad	ET	GrassGro
ET	S 1	0.560**	0.225**	0.610**	−0.126*	0.532**	0.483**	0.909**	1	0.659**
	S 2	0.920**	0.492**	0.524**	−0.288**	0.858**	0.824**	0.754**	1	0.338**
	S 3	0.695**	−0.032	0.593**	−0.370**	0.577**	0.423**	0.747**	1	−0.071
	S 4	0.885**	0.649**	0.751**	−0.148**	0.863**	0.853**	0.958**	1	0.736**
GrassGro	S 1	0.609**	0.433**	0.188**	−0.116	0.629**	0.624**	0.478**	0.659**	1
	S 2	0.342**	0.279**	0.107	−0.046	0.352**	0.336**	0.213**	0.338**	1
	S 3	−0.379**	−0.045	−0.186**	0.151**	−0.145*	−0.148**	−0.041	−0.071	1
	S 4	0.664**	0.516**	0.421**	−0.156**	0.685**	0.663**	0.692**	0.736**	1

Note: Variables were maximum temperature (MaxT), minimum temperature (MinT), sunshine hours (Sun), rainfall (Rain), soil temperature at 50 mm (SoilT50), soil temperature at 100 mm (SoilT100), solar radiation (SolRad), evapotranspiration (ET) and grass growth rate (GrassGro). Significance: $*P < 0.05$, $**P < 0.01$.

Table 4. Seasonal multiple regression analysis of weekly independent meteorological variables with weekly grass growth as dependent variable. (a) All meteorological variables without ET.

	Variables	Coefficients	t	Tolerance	VIF	F-test	Adjusted R^2	Standard error
Season one	(Constant)	−31.20	−7.04**			63.06**	0.499	14.18
	SoilT50	5.94	10.12**	0.914	1.094			
	SolRad	0.03	5.748**	0.907	1.103			
	Rain	−0.94	−2.17*	0.981	1.019			
Season two	(Constant)	48.77	9.00**			43.38**	0.121	22.42
	SoilT50	2.83	6.59**	1.000	1.000			
Season three	(Constant)	111.40	8.78**			29.54**	0.271	18.80
	MaxT	−6.59	−7.50**	0.383	2.613			
	SolRad	0.06	6.49**	0.163	6.118			
	Sun	−5.66	−4.03**	0.134	7.440			
	MinT	3.20	3.56**	0.509	1.966			
Season four	(Constant)	−4.45	−2.62*			216.06**	0.612	10.44
	SolRad	0.09	17.53**	0.242	4.139			
	Sun	−8.48	−9.78**	0.242	4.139			

(b) All meteorological variables with ET.

	Variables	Coefficients	T	Tolerance	VIF	F-test	Adjusted R^2	Standard error
Season one	(Constant)	−33.86	−8.29**			104.91**	0.526	13.79
	ET	23.95	7.48**	0.694	1.411			
	SoilT100	4.35	6.20**	0.694	1.411			
Season two	(Constant)	48.77	9.00**			43.38**	0.121	22.42
	SoilT50	2.83	6.59**	1.000	1.000			
Season three	(Constant)	145.54	13.39**			38.04**	0.326	18.08
	MaxT	−12.65	−11.46**	0.224	4.463			
	ET	26.17	8.37**	0.375	2.666			

Table 4 (*Continued*)

	Variables	Coefficients	t	Tolerance	VIF	F-test	Adjusted R^2	Standard error
	MinT	6.68	7.09**	0.429	2.332			
	Sun	1.55	2.13*	0.458	2.181			
Season four	(Constant)	−8.19	−4.17**			176.51**	0.563	11.08
	ET	17.51	13.68**	0.729	1.371			
	MinT	1.02	3.89**	0.729	1.371			

Note: Independent variables were maximum temperature (MaxT), mean temperature (MeanT), minimum temperature (MinT), sunshine hours (sun), rainfall (rain), soil temperature at 50 mm (SoilT50), soil temperature at 100 mm (SoilT100) and evapotranspiration (ET). Significance: $*P < 0.05$, $**P < 0.01$. Unstandardized coefficients: regression coefficients provide the value of the Y-intercept (labelled 'constant') and the slope representing the effect of the independent variables on the dependent (grass growth); t = t value for the coefficient with two-tailed significance level of t; tolerance = if close to 1 means there is little multicollinearity, whereas a value close to 0 suggests that multicollinearity may be a problem; VIF = variance inflation factor. VIFs above 10 are usually considered to indicate serious multicollinearity. Serious multicollinearity greatly increases the estimation error of the model coefficients; F-test = if significant indicates that the model predicts significantly more variability in the dependent variable compared to a null model that only has an intercept parameter; adjusted R^2 = a measure of model fit, adjusting for the number of independent variables in the model; standard error of the estimate = the standard deviation of the residuals.

weather trend in Ireland difficult due to its influence (McElwain and Sweeney 2003). The analysis indicates an increase in air temperature (maximum, minimum and mean) of approximately 0.5°C at Moorepark over the period 1982 to 2010. However, these increases were not statistically significant, and the period of analysis would be considered small for climate analysis. Using longer time series, McElwain and Sweeney (2003) and Butler *et al*. (2007) found significant increasing trends in temperature over the twentieth century, in agreement with results obtained at a global scale (0.6°C ± 0.2; IPCC 2001). The results in the increased mean temperature found at Moorepark could be explained because the rate of warming has been doubled in the last 50 years (McElwain and Sweeney 2007). All air temperatures experienced a decrease in July and in December at Moorepark, the latter more apparent from 2007 (data not shown). Soil temperature least square regression lines at Moorepark had steeper slopes when compared to air temperatures (0.045 compared to 0.016 on average per month), meaning that the increase in soil temperature is faster than the increase in air temperature (Table 2, Figure 2). These results are similar to other findings in Ireland; Butler *et al*. (2007) reported that over the past century soil temperatures at both 30 cm and 100 cm increased about twice as fast as air temperature over the same period at Armagh in Northern Ireland.

The analysis by the IPCC (2001) found a small increasing global trend in precipitation yearly and seasonally over land during the twentieth century. Allan *et al*. (2009) found a correlation between severe storms in the winter period (January to March) and the NAO from 1920 to 2004, but the strength of the correlation fluctuated from almost zero in 1950 to 1970 to a maximum value in 1970 to 1990. Murphy and Washington (2001) studied the relationship between the precipitation variability in the UK and Ireland, and the North Atlantic sea-level pressure field and found strong positive correlations between the NAO and precipitation in the northwest of the UK and Ireland, particularly in winter, but no significant correlations in the southeast during all months.

Average annual precipitation over the 29-year period studied at Moorepark shows a small but non-significant negative trend similar to non-significant decreases at Roche's Point and Rosslare in the South of Ireland (McElwain and Sweeney 2003), while precipitation has increased in the north of the country at Malin Head (McElwain and Sweeney 2003) and Armagh (Butler *et al*. 2007). These results suggest that in Ireland annual precipitation is increasing in the north of the country and decreasing in the south. Considering the monthly data, the greatest increases in precipitation observed at Moorepark were in July and November, and decreases in February, March, June, August, October and December were observed; none of the patterns were significant except July. The wettest months at Moorepark were January, October and November, and the driest were April, May and July. However, McElwain and Sweeney (2003) reported that long-term monthly records of precipitation in Ireland show that February, March and October were the wettest months and seem to be getting wetter, while May, August and September tend to be the driest. Changes to precipitation patterns are more spatially and seasonally variable than temperature changes (McElwain and Sweeney 2007), so a comparison of changes in trends of precipitation among sites would be more difficult than a comparison of air temperatures.

The results of sunshine hours in the analyses reported in this paper differ with data for Northern Ireland (years 1886–2003) reported by Butler *et al*. (2007) who found significant negative trends in sunshine hours, but it is important to note that Armagh observatory is in Northern Ireland, while Moorepark is situated in the South of Ireland. This suggests that sunshine hours might be decreasing in the north of Ireland and increasing in the south.

In the study reported in this paper there were significant increases in solar radiation at Moorepark in March, April, June and August. Annual solar radiation showed a positive significant trend at Moorepark consistent with the significant increase in sunshine hours. Stanhill (1998) analysed the trends in global radiation from 1954 to 1995 at eight different locations in Ireland and found negative trends at three of them (Valentia, Kilkenny and Birr) and a positive trend at Dublin airport, but this increase was not in accordance with the decrease shown in sunshine. Black *et al*. (2006) found a significant positive trend in solar radiation at Belmullet station from the 1980s, but at the other three stations studied (Valentia, Kilkenny and Birr) prior to 1984 there were significant negative patterns. This study at Moorepark has similar results to Black *et al*. (2006), providing more evidence of the cessation or reversal of the decline in solar radiation since the 1980s at some locations in Ireland.

The principal weather parameters affecting ET are radiation, air temperature, humidity and wind speed (Allen *et al*. 1998). ET was highly correlated with solar radiation in seasons one and four. There was a positive significant annual trend in ET at Moorepark. Monthly records show increases in ET in all months at Moorepark except July and August when the greatest mean temperatures were registered (Table 1) and significant increases in October and November (data not shown). During the months May to August ET was, on average, greater than rainfall (data not shown). ET is important because as soil dries out the remaining water is held more tightly in micro-pores and plants experience increasing difficulty in extracting water from the soil (Collins *et al*. 2004). The plants respond by closing the stomata which reduces the diffusion rate of water molecules, and as the stomatal resistance increases, ET is checked or reduced (Collins *et al*. 2004). The greatest values of ET occurred in June and July, in accordance with the fact that ET is low in winter when solar radiation is low and it reaches its maximum value in midsummer (Collins *et al*. 2004).

As stated before, the period examined in this study is considered to be short for climate analysis. The patterns found could be due to the cycles of climate. Butler *et al*. (2007), using wavelet analysis, found significant cycles with periods of 7–8 years, 20–23 years and 30–33 years in the seasonal and annual meteorological series from Armagh (Northern Ireland), and some of these cycles were clearly linked to the NAO. Therefore, it is possible that the patterns observed in the 29-year data-set analysed in this study could also reflect climatic cycles rather than climate change.

Grass growth data

The start and end of grass growth measurements varied between years; there was a large variation in the date on which grass growth measurement commenced each year, from week 3 in 2010 to week 13 in 1986. Variability of grass growth within and between years can be due to meteorological conditions, but management and crop variety also influence grass growth. In this study the same management, apart from measurement start date, was applied in all years, so it was not considered a possible factor affecting grass growth rate. Weather influences the growth of crops in two different ways; setting limits on the length of the growing season, and controlling growth rates during the growing season (Burke *et al*. 2004). The number of days required from 1 January for grass growth to begin varied from 36 to 113 days over the period at Moorepark, on average 64 days (4/5 March) were necessary to produce 10-kg DM/ha/day over the 28 years. Extremes of weather, such as low temperatures in spring and low rainfall in summer, can limit the length of the grass growing season. Extremes at other times can also have an effect on yield, for example, extremes of wind and rain at harvest (Burke *et al*. 2004) and drought conditions.

Soil temperature plays an important role in grass growth. Connaughton (1973) used a threshold of 6°C soil temperature at 100 mm to calculate the median dates for the commencement of the grass growing season, and published the dates on a map of Ireland where Moorepark appears to be in the period 1–15 March. Grass growth starts at Moorepark on the 5 March on average, within the period proposed by Connaughton (1973). The number of days required to start grass growth seem to be decreasing, this might be one of the consequences of the effect of climate change on grass growth. There is evidence of this in a study in Europe examining the relationship between air temperature and the start of the growing season which showed that between the early 1970s to the late 1990s the mean spring temperature (February to April) increased by 0.8°C and the average of the beginning of the growing season advanced eight days (Chmielewski and Rötzer 2002).

Relationship between meteorological and grass growth data

Soil temperature has a major influence on the growth and development of plants and is often the determining factor in plant production. Low temperatures inhibit the growth of grass (Figures 4–7). Perennial ryegrass requires a period of low temperature and short days (vernalisation) before it can respond to environmental factors to begin reproductive initiation (Aamlid *et al*. 2000). Grass growth is generally considered to only occur at temperatures above 5°C (Hopkins 2000b); however, it is likely that when other meteorological conditions are favourable some grass growth can occur at temperatures below 5°C. The temperature of the soil depends primarily on solar radiation (Keane and Sheridan 2004). Although sunshine hours were only important in seasons three and four (Table 4a and 4b), they would have had an influence on air and soil temperature in the other seasons through solar radiation. Soil temperature at both 50 mm and 100 mm depths showed an increase over the period of analysis that could have a consequence for the length of the grass growing season. This indicates that the grass growing season might be getting longer, and therefore more grass growth and thus cheaper feed for dairy cows may be the norm in future.

Grass growth was related to maximum temperature, minimum temperature, soil temperature at 50 mm and at 100 mm, solar radiation and ET in seasons one and four and also to sunshine in season four. In seasons one and four, low temperature and low solar radiation limit grass growth. No strong relationship was found between grass growth and rainfall in any of the seasons. This might indicate that water deficit or waterlogging were not a problem, except for example, May 1991 and the summers of 1995 and 2006 which were very dry periods and grass growth recorded was very low. Previous studies on the relationships between the annual grass growth potential and meteorological records found that the addition of mean temperatures and mean light and subtraction of the mean daily rainfall was highly correlated with the annual changes in grass productivity (Meehan and Gilliland 2011).

Implications

There is interest in specifying the role of climate on grass growth but there is a need for a model to take account of the interactions between climate, grass physiology and other factors influencing grass growth. Rather than an empirical approach, such as that examined in this study, a mechanistic model, incorporating meteorological influences on grass growth, as well as other aspects influencing grass growth (e.g. soil type, water availability, plant tissue turnover; Hennessy *et al*. 2008) could improve the simulation of grass growth. A mechanistic model requires universal parameters and given the correct inputs, it is likely to be effective across a range of conditions and sites (Thornley 1998). Empirical models, in contrast, are most accurate at the site at which they were developed, and their accuracy declines with increasing distance from that site (Holden 2001).

Conclusion

Monthly significant weather patterns were found in all the meteorological variables studied (maximum, minimum and mean air temperature, soil temperature at 50 mm and at 100 mm, sunshine hours, solar radiation and rainfall). Different meteorological factors influence grass growth at different times of the year. Major factors identified as affecting grass growth in this study are soil temperature, air temperature and ET. The start date of grass growth was 64 days on average. These results suggest that it may be possible to use meteorological data to predict grass growth, although management factors will also contribute to grass growth rate. The study supports the hypothesis that climate patterns occur in Ireland and that it might have future consequences on the rate of grass growth and on the farm management needed. There is interest in specifying the role of climate on grass growth but there is a need for a model to take account of the interactions between climate, grass management and utilisation. A robust grass growth model which uses meteorological data as an input is likely to be mechanistic rather than the empirical approach, as examined here.

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