The influence of weather on early growth rate of grasses

GUÐNI THORVALDSSON

HÓLMGEIR BJÖRNSSON

AND

JÓNATAN HERMANNSSON

Agricultural Research Institute, Keldnaholti, IS-112 Reykjavík
E-mail: gudni@rala.is
E-mail: holmgeir@rala.is
E-mail: jonatan@rala.is

SUMMARY

Weekly yield measurements from the onset of growth in May over 4 to 7 weeks during a period of 13 years were used to estimate the effects of weather on the early growth rate of grasses. The growth rate and weekly mean of weather variables were calculated for each week. In addition to radiation or precipitation for the respective week these variables from the preceding week were found to influence the growth rate. The average growth rate was 52 kg DM ha^{-1} day^{-1}, ranging from 4 to 144 kg ha^{-1} day^{-1}. Increasing growth rate during spring followed the exponential growth curve. The estimated effect of mean temperature and radiation on growth rate was 8.5 kg DM ha^{-1} day^{-1} $°C^{-1}$ and 4.4 kg DM ha^{-1} (MJ $m^{-2})^{-1}$ respectively, and the effect of radiation in the preceding week was estimated at 2.5 kg DM ha^{-1} (MJ $m^{-2})^{-1}$. Soil water supply was measured indirectly as rainfall and was represented by five parameters in the regression model. The effect of precipitation on growth rate during the week of measurements was 49 kg DM ha^{-1} mm^{-1} up to the threshold level of 1.0 mm day^{-1} and in the preceding week 10.2 kg DM ha^{-1} mm^{-1} up to the threshold level 2.8 mm day^{-1}. The effect of distribution of rain on growth rate, represented as number of days with rain each week, was also significant. Despite the stromg influence of weather on growth rate within years, weather variables only explained a part of the variation in growth rate between years. The regression on winter temberature was not significant..

Key words: grasses, growth rate, temperature, radiation, precipitation

YFIRLIT

Áhrif veðurs á sprettu grasa fyrri hluta sumars

Vikulegar mælingar á sprettu voru gerðar á tilraunastöðinni Korpu á þréttán ára tímabili. Mælingarnar hófust strax og hægt var að mæla uppskeru í maí og stóðu í 4-7 vikur. Þessar mælingar ásamt veðurgögnum voru notaðar til að meta áhrif veðurþátta á sprettu. Meðalspretta var 52 kg þe. ha^{-1} dag^{-1} og sveiflaðist frá 4 til 144 kg þe. ha^{-1} dag^{-1}. Spretta fylgdi veldisvísisvexti með tíma. Áhrif hita á sprettu mældust 8,5 kg þe. ha^{-1} dag^{-1} $°C^{-1}$og geislunar 4,4 kg þe. ha^{-1} (MJ $m^{-2})^{-1}$. Geislun vikuna á undan hafði einnig áhrif og stuðullinn mældist 2,5 kg þe. ha^{-1} (MJ $m^{-2})^{-1}$. Úrkoma var notuð sem mælikvarði á vatn í jarðvegi bæði sprettuvikuna og vikuna á undan. Fimm stuðlar voru notaðir í líkaninu til að meta áhrif hennar. Reiknuð voru út þröskuldsgildi þannig að úrkoma upp að þröskuldsgildinu hafði línuleg áhrif en úrkoma umfram það engin áhrif. Þröskuldsgildi sprettuvikuna var 1,0 mm dag^{-1} og 2,8 mm dag^{-1} vikuna á undan. Þröskuldsgildi sprettuvikuna var 1,0 mm dag^{-1} og 2,8 mm dag^{-1} vikuna á undan. Stuðull fyrir úrkomu sprettuvikuna mældist 49 kg þe. ha^{-1} mm^{-1} upp að þröskuldsgildinu 1 mm dag^{-1} og stuðull fyrir vikuna á undan mældist 10,2 kg þe. ha^{-1} mm^{-1} upp að þröskuldsgildinu 2,8 mm dag^{-1}. Fjöldi rigningardaga í viku hverri hafði einnig áhrif á sprettuhraðann. Þrátt fyrir mikil áhrif veðurs á vaxtarhraða innan árs, skýrðu veðurþættir aðeins hluta af breyrileikanum í vaxtarhraða milli ára. Áhrif vetrarhita á sprettuhraða voru ekki marktæk..

INTRODUCTION

The yield of a grass crop is a function of the growth rate throughout the season. The growth rate is controlled by genetic as well as environmental factors such as weather, soil and management factors including fertilization. Models for the simulation of growth of different plant species have been developed during recent decades, based on the available knowledge and understanding of the interaction between the plant and the environment (Baier 1973, Bouman *et al.* 1996). In northern areas the proportion of forage in animal feed is often very high. The quality of forage is therefore of great importance in these areas and models simulating the relationship between weather and growth have been developed (Torssell & Kornher 1983, Gustavsson *et al.* 1995, Bonesmo 1999, Bonesmo & Bélanger 2002).

Icelandic experimental results provide information on the relationship of grass growth to environmental factors such as cutting dates during the preceding summer (Björnsson & Helgadóttir 1988, Brynjólfsson 1994), temperature during the winter (Bergthórsson 1966, Björnsson & Helgadóttir 1988, Thorvaldsson & Björnsson 1990) and the effects of weather in the growing period on growth rate and quality (Thorvaldsson & Björnsson 1990, Thorvaldsson *et al.* 2000). Temperature effects on growth rate at different growth stages of grasses were studied in growth chamber experiments (Thorvaldsson 1992, Thorvaldsson & Martin 2004).

The aim of the present study was to gain knowledge on the relationship between weather and early growth. The onset of grass growth and early growth rate were observed in an experiment with timing of fertiliser application at the Korpa experimental station (Lat. N 64° 09' and Long. W 21°45') and the results were analysed for factors affecting the onset of growth and for yield (Thorvaldsson 1998). In this paper we use results from this experiment over a period of 13 years to analyse and quantify the relationship between growth rate of grasses and weather factors in spring and early summer (May-June).

MATERIALS AND METHODS

The experiment

The experiment was located on an old grass field with mixed vegetation. The most abundant species were *Festuca rubra* L. (40 %), *Poa pratensis* L. (20 %), *Agrostis capillaris* L. (20 %), *Deschampsia caespitosa* (L.) Beauv. (10 %), *Trifolium repens* L. (10 %). Other species were *Phleum pratense* L., *Alopecurus pratensis* L., *Taraxacum vulgare* Schrank., *Cerastium fontanum* Baumg. and *Alchemilla vulgaris* L. Changes in botanical composition were small during the experimental period although *Festuca rubra* increased a little and *Poa pratensis* decreased. Underlying the field is a layer of sand pan at a depth of 25-35 cm. Table 1 shows several soil characteristics, the mean of six sample profiles, to 26 cm depth. The soil is an andosol, rich in organic matter, with characteristic low bulk density. The soil was sampled shortly after heavy rainfall in July 2002 and the actual water content used as a measure of field capacity. Plant available water is found by subtracting the water content at the wilting point measured with 15 atm. pressure in the laboratory.

The experiment included four treatments in three replicates, a treatment without fertilization and three dates of fertilizer application: in the autumn, before onset of growth in spring, and after onset of growth in spring. Plot size

Table 1. Physical properties of the soil profile.

Soil depth	Bulk density of undisturbed soil, g cm^{-3}	Fine soil, < 2 mm, weight %	Water at field capacity, mm m^{-2}	Plant available water, mm m^{-2}
0-10 cm	0.51	93	59	34
10-20 cm	0.70	89	58	38
20-26 cm	0.76	53	35	21
Total (0-26 cm)			152	93

was 2.5 x 10 m. The amount of fertilizer used was 90 kg N, 20 kg P, 37 kg K, 16 kg Ca and 9 kg S ha^{-1} $year^{-1}$. The plots were observed weekly from early spring and graded for green colour until the plots were fully green. The yield was measured weekly by clipping two strips, 10 cm wide and 2 m long, in each plot, beginning as soon as growth permitted and continued until late June. The measurements were not taken at fixed locations. In early August the plots were harvested and the yield measured. The observations on onset of growth and yield measurements for the first 8 years were presented by Thorvaldsson (1998). Similar presentation for all years as well as nitrogen analyses of samples from the experiment will be published later.

The growth curve was, with few exceptions, parallel for the three application dates, meaning that timing of fertilisation has rather little effect on growth rate relative to other sources of variation (Thorvaldsson 1998). The precision of yield measurements was rather low and, in order to get more stable results for the analysis, the average over all fertilized plots was used as a measure of yield and the growth rate was calculated by calculating the differences between subsequent yield measurements. The differencing introduces negative autocorrelation between adjacent weeks within years. Occasional initial observations in spring, when the dry matter (DM) was below 90 kg ha^{-1} in the second mesurement, were omitted and so were high values in late June that exceeded 3000 kg DM ha^{-1}. Two outlying yield measurements were considered to be in error, each invalidating two measures of growth rate. The remaining total number of observations on growth rate for the analysis was 68. The period of observations that were used lasted four to seven weeks, beginning on average May 20 (May 7 - May 30) and ending in mid or late June.

Weather observations

Temperature and precipitation were measured at the Korpa experimental station ca. 100 m away from the experiment. Radiation was measured at the Reykjavík weather station, at a distance of 8 km. The weather variables were temperature (°C), radiation (MJ m^{-2}) and precipitation (mm), all expressed as mean per day in a week (Table 2). In addition to weather variables for the respective week it was found that

Table 2. Weekly means and range of weather variables.

	Mean	**Minimum**	**Maximum**
Temperature °C	8.1	0.9[1]	11.1
Radiation, MJ m^{-2} day^{-1}	15.9	7.6	25.0
Precipitation, mm day^{-1}	2.0	0.0	7.3
Frequency of precipitation, days $week^{-1}$	4.6	0	7

[1] Excluding a single extremely low value, the range is 4.0 to 11.1°C.

these variables from the preceding week influenced the growth rate. Other variables tested for inclusion in the regression model included soil temperature and maximum and minimum air temperatures.

Measures of soil moisture deficiency indicating the water supply for growth (Torssell *et al.* 1982) have not been developed for the site. Precipitation was an indirect measure of the water supply and its effect on growth depended on the quantity and distribution relative to the soil water deficiency. Precipitation exceeding the immediate needs for growth did not favour grass growth until at a later date so that the relation to grass growth was nonlinear. This was modelled by allowing a linear effect of precipitation on growth rate up to a threshold level and no effect above that level. The threshold level was found to be 1.0 mm day^{-1} and 2.8 mm day^{-1} for precipitation in the week measured and in the previous week respectively. The number of observations exceeding the thresholds was 43 and 17 respectively, and the mean of the new variables formed by reducing higher values to the threshold levels was 0.83 and 1.61 respectively. The number of days with precipitation within the week was included as a variable that measured the effect of the distribution of rainfall.

Statistical analysis

Growth rate was analysed in a regression model of the general form *y=f(A,t,w)*, where ***A*** represents year effects that are not explained by regression within years, ***t*** represents variables that describe the increasing growth rate during initial spring growth, and ***w*** represents weather variables that affect growth rate. The year effects were modelled in two different ways. The first treated them as fixed effects:

$$y_{ij}=A_i + \Sigma_h b_h x_{hij}+e_{ij}$$

where y_{ij} is the observed growth rate in week j, j=1, 2 ... (4, 5, 6, or 7) in year i, i = 1990, 1991 ... 2002, A_i is the expected mean growth rate in year i, and b_h is the expected regression coefficient of growth rate on variable x_h, where h=1, 2 ... k and k is the number of variables in the model. The residuals, e_{ij}, have equal variances, σ^2, and zero covariances, except Cov(e_{ij} , e_{ij+1}) = -0.5 σ^2. This is the first order moving average error model, MA(1), with the first order autocorrelation coefficient $\mathbf{r_1}$ = -0.5 due to differencing (Box & Jenkins 1970). In the phase of selecting weather variables for inclusion in the regression model ordinary least squares equations were used, ignoring the correlated error structure. This approach gives unbiased estimates but they are not efficient and the error of coefficients is slightly overestimated.

The second approach is the random effects model with year effects random, a split-plot-like model. Since year effects are no longer fixed, the variation between years is included in the estimation of regression coefficients. In order to obtain unbiased estimates of regression of spring growth, the model should include all variables that explain the variation in growth rate between years, unless the variables modelling growth rate in spring are orthogonal to the residual year effects. Several combinations of temperature during the winter months were tested for inclusion in the model.

The model with years fixed and moving average errors within years was fitted using the Reml directive in Genstat (Payne *et al.* 2000). Weeks within years were expanded into a single factor with 68 levels and declared as a random error component. A symmetric matrix of rank 68 was created with 1 on the diagonal and -0.5 on the subdiagonals for observations within years and zero in all other positions. This matrix was used as a correlation matrix to define the covariance model in the Vstructure directive in Genstat. In the model with year effects random the variance components were years and weeks within years with MA(1) covariance model within years.

Variables in class ***w*** were presented in an earlier section. In class ***t***, representing increasing growth rate in spring, there are two variables: days from the onset of growth and yield calculated as the mean of the yield measurements at

Table 3. Regression of growth rate, kg DM ha^{-1} day^{-1}, on yield, time and weather variables.
Coefficients of regression = **b,** and their standard error = s_b.

Independent variables in regression	Year effects fixed: t = yield B	s_b	t = days b	s_b	Full model b	s_b	Year effects random b	s_b
Yield, DM hkg ha^{-1}	2.8	0.46			2.6	0.42	3.9	0.43
Days from onset of growth			1.6	0.30				
Weather the same week								
Mean temperature, °C	9.2	1.9	8.8	2.2	8.5	1.7	6.6	1.6
Radiation, MJ m^{-2} day^{-1}	3.5	1.04	3.3	1.10	4.4	0.99	1.7	0.73
Precipitation, max. 1.0 mm day^{-1}	47	14	47	15	49	13	27	1.04
Number of days with precipitation	3.0	2.6	1.5	2.7	5.3	2.5		
Weather the week before								
Precipitation, max. 2.8 mm day^{-1}					10.2	3.0	3.6	2.4
Radiation, MJ m^{-2} day^{-1}					2.5	0.82		
Mean temperature °C							-3.7	1.4
Standard deviation	18.4		19.6		16.6			
$\mathbf{r_1}$ of the residuals	-0.17		-0.23		-0.17		0.07	

the beginning and end of the respective week. Yield was on average 96 kg DM ha^{-1} in the first week of observations and ranged from 1080 to 2460 kg DM ha^{-1} in the final week of observations included in the data set. These measures of yield and the growth rate are statistically independent because they are calculated as the mean and difference, respectively, of the same measurements. Therefore they can be used as the independent and dependent variables, respectively, in the regression analysis for estimating their functional relationship. The great variability between years in maximum yield causes confounding between yield and year effects. Linear regression of growth rate on days and yield estimates growth rate in a quadratic and an exponential growth curve respectively.

RESULTS

The average growth rate in the data analysed was 52 kg DM ha^{-1} day^{-1}. The range was from 4 to 144 kg DM ha^{-1} day^{-1} and the standard deviation 35. The results of the regression analysis of growth rate in spring, modelling this variation, are presented in Table 3. The regression model with MA(1) errors and year effects giving best fit, hereafter called the *full model***,** includes precipitation and radiation in the week before measurements in addition to yield and weather variables in the same week, and the coefficients of this model are used in the discussion of results. Results are also shown without weather variables in the week before, and with days instead of yield. The variable selection with random year effects differs slightly. The regression on winter temperature was not significant and is not shown. Measures of the residual variation are shown as standard error ($\mathbf{s_b}$) of regression coefficients (**b**), standard deviation from the regression ($\mathbf{s_{y.x}}$) and autocorrelation ($\mathbf{r_1}$) of residuals lagged one week within years. Models with yield for describing the increasing growth rate from early to late spring gave better fit than models with days and the inclusion of days after yield did not improve fit. The inclusion of weather data from the previous week improved fit considerably. Only temperature the preceding week did not give a significant contribution, the coefficient being 1.6±2.1 kg ha^{-1} °C^{-1} when added to the full model.

When fitted by ordinary least squares the first order autocorrelation within years, $\mathbf{r_1}$, of residuals in the full model is -0.40 and $\mathbf{r_2}$ and $\mathbf{r_3}$, autocorrelations lagged two or three weeks, were -0.01 and -0.19 respectively. These values were close to the theoretical values -0.5, 0.0 and 0.0 respectively for a MA(1) process. In this case $\mathbf{r_1}$ was calculated on 55 pairs of values with an approximate one standard error unit wide interval of -0.36 to -0.62. The autocorrelation of residuals in the full model was -0.17. The standard error was 0.17 so that the autocorrelation did not differ significantly from the theoretical value of zero. The results indicate that there were no major lagged functional relationships remaining to be modelled.

No significant results were obtained by regression on winter temperature in the random year effects model, contrary to earlier findings. The estimated variance of year effects for the model shown in Table 3 was 2.5^2. Among the independent variables, yield in particular was partially confounded with year effects. Leaving this variable out of the regression model, the variance component for years was 21.0^2. Based on the fixed effects model an approximate estimate of the between years component of variance of growth rate was 17^2. This estimate was obtained by subtracting half the average error squared of differences between years from the variance of estimated year effects. This variance component is an estimate of the variation between years that remained when the growth rate within year had been modelled. The variance of a randomly selected week was then $24^2=(17^2+16.6^2)$, i.e. the sum of the years components and the residual standard deviation, and it was 47% of the variance in the raw data with s=35. Residual plot did not indicate any clear tendency to increasing variability with increasing yield.

The predicted value of growth rate when all independent variables were at their mean value was the mean of the data set, 52 kg DM ha^{-1} day^{-1}. The mean yield was 770 kg DM ha^{-1}. As it increased from 100 to 2500 kg DM ha^{-1} the growth rate was predicted to increase from 34 to 97 kg DM ha^{-1} day^{-1}. At the upper end of the growth curve there were only few values exceeding 1700 kg ha^{-1}. In five of the 13 years the final yield measurements exceeded 2000 kg ha^{-1} and the growth rate was then 111 kg DM ha^{-1} day^{-1} on average. Temperature and radiation were higher by the end of June than earlier in spring so that the observed growth rate was higher than predicted by yield alone. The growth curve was expected to be exponential only up to a certain yield level. Models with growth rate becoming linear at a lower level, i.e. with a threshold value for yield, and models with nonlinear terms for deviations from the exponential model were tested. None of these models gave improved fit.

The range in predicted effects on growth rate over the observed range in weekly weather variables, i.e. precipitation with threshold value and number of days with rainfall, temperature (excluding the lowest extreme value, see footnote of Table 2), and radiation, was 86, 61 and 76 kg DM ha^{-1} day^{-1}. When the effect of rainfall and radiation in previous week was included the range in predicted effects for these weather factors increased to 108 and 107 kg DM ha^{-1} day^{-1}, respectively. The effect of precipitation was not linear and therefore not symmetric about the means. During the average week, the combined predicted effect of rainfall and number of days with precipitation was 67 kg DM ha^{-1} day^{-1}, not including the effect of rainfall the week before. While excessive moisture had no beneficial effect, growth was retarded when soil moisture was limiting. This would in particular apply to 8 of the 68 weeks in the data set when the predicted effect was below 50, and in 14 weeks it was below 65 kg DM ha^{-1} day^{-1}. In the remaining 54 weeks the effect of water deficit during the week was small, i.e. the predicted values were all within a narrow range near the maximum and uncertain because the regression was a linear approximation to a nonlinear process.

Precipitation is represented by a total of five parameters in the regression model, including the two threshold levels introduced. Added to the effect of precipitation during the week measured is the residual effect of rain the week before. The representation of rainfall as weekly values is arbitrary and beneficial effect of heavy rainfall can only be expected when a dry period follows. This implies interaction between weeks. This was tested and found statistically significant by including a multiple of the two precipitation terms in the regression model.

It is important to keep in mind that radiation is closely related to temperature and precipitation. On a cloudy day the difference between the temperature maximum and minimum is less than on a bright day. On a bright day the temperature of the growing leaves is expected to be higher than temperature measured 2 m above ground level, while on a cloudy and rainy day this is not the case. In a regression analysis it is not possible to distinguish between, for example, direct effects of rainfall and the indirect effect through less radiation and lower temperature in the canopy.

DISCUSSION

According to these results maximum growth rate occurs on relative warm, sunny days in a period with frequent rainfall. This is in agreement with the general feeling for good growth conditions for grass in Iceland.

Einarsson (1972) calculated the potential evapotranspiration in Reykjavík and found it to be about 3 mm day^{-1} in May and June. The precipitation during the experimental period was on average 2 mm day^{-1}, giving a negative potential water balance of the order of 1 mm day^{-1}. The soil in this experiment is capable of storing about 93 mm of plant available water down to 26 cm of the soil profile (Table 1). The strong effects of precipitation found indicate that water deficit was occasionally limiting for grass growth but most of the time the deficit was rather small. Grass roots are shallow at early growth stages. This is a likely explanation to the significance of frequent rainfall. Frequent rain could then be required for rapid grass growth although there may still be plenty of water deeper in the soil profile. The observed effect of days with rainfall could also be partly artificial, caused by events such as all rainfall falling on the last day of the week.

Thorvaldsson & Björnsson (1990), summarized growth rate from many Icelandic experiments. During the period June - August the average growth rate was 71-114 kg DM ha^{-1} day^{-1}, depending on the species. Using an estimated rather than observed date for the start of growth the average growth rate before first cut, usually in late June, was 86 kg DM ha^{-1} day^{-1} for *Phleum pratense* and 58 kg DM ha^{-1} day^{-1} for *Poa pratensis.* These earlier findings compare well with the average growth rate of 52 kg DM ha^{-1} day^{-1} in this experiment, although determined by a different approach.

Thorvaldsson & Björnsson (1990) estimated the effects of weather parameters on growth rate in mid-summer following first harvest, using results from harvest time experiments of *Phleum pratense* and *Poa pratensis*. For *Phleum pratense* the results for effects of temperature and radiation respectively were 8.1±2.9 kg DM ha^{-1} day^{-1} °C^{-1} and 5.9±1.8 kg DM ha^{-1} (MJ m^{-2})$^{-1}$ up to the level 17 MJ m^{-2} day^{-1}. These results are in good agreement with the results presented here and so are the results from another experiment with *Phleum pratense* at the experimental station at Korpa which gave the coefficients 8.5±4.3 kg DM ha^{-1} day^{-1} °C^{-1} and 5.6±1.7 kg DM ha^{-1} (MJ m^{-2})$^{-1}$ (unpublished). The effects of temperature and radiation were not as clear for *Poa pratensis* in that experiment even though the same trend was found.

In a growth chamber experiment with seven different species, it was found that a temperature increase from 9 to 13 °C increased the growth rate by 4.3 kg DM ha^{-1} day^{-1} °C^{-1} (11%) for each degree of change (Thorvaldsson & Martin 2004). The average growth rate was 40 kg DM ha^{-1} day^{-1}. In an earlier growth chamber experiment with timothy the coefficient was 7.4 kg DM ha^{-1} day^{-1} °C^{-1} in the interval 8 to 12°C (Thorvaldsson 1992). The average growth rate in that experiment was 126 kg DM ha^{-1} day^{-1}. These results support the findings of the present paper, although results from growth chamber experiments are not directly applicable to outdoor conditions.

It is of interest to find significant effects of radiation during the previous week on growth rate. This finding indicates that growth rate is not only a result of the weather during the current week but also of the weather earlier in the growth period. Results from growth chamber experiments indicate that young grass seedlings at early growth stages respond more directly to temperature changes than do older plants (Thorvaldsson 1992, Thorvaldsson & Martin 2004). It can take a long time for mature plants to show any effects of temperature change on the growth rate.

Earlier studies have shown a strong relationship of grass yield in summer to temperature the preceding winter (Bergtþórsson 1966, Bergthorsson 1988, Björnsson & Helgadottir 1988, Thorvaldsson & Björnsson 1990). An explanation of this effect is that warm winters are followed by a longer growing season, including a longer period for active mineralization of nitrogen, and that this increased availability of nitrogen increases the potential for grass growth (Björnsson 2004). Significant effects of winter temperature on growth rate were not found in this investigation, thus providing further support to the idea that it is the length of the season rather than growth rate or rate of mineralization that is affected by winter temperature. The rate of nitrogen mineralization, on the other hand, may vary between years. This could be the reason for different growth rates between years since the nitrogen application, 90 kg N ha^{-1}, is suboptimal so that added nitrogen would increase growth rate and, *vice versa*, more nitrogen uptake is required for increased growth.

ACKNOWLEDGEMENTS

This work was partly supported by grants from the Icelandic Council of Science, Reykjavík.

REFERENCES

Baier W 1973. Crop-Weather Analysis Model: Review and Model Development. *Journal of applied Meteorology*, 12, 937-947.

Bergþórsson P 1966. Hitafar og búsæld á Íslandi [Temperature and wellbeeing in Iceland]. *Veðrið* 11(1),15-20. (In Icelandic).

Bergthórsson P 1988. The effect of climatic variation on agriculture in Iceland. Section 2: The effects on agricultural potential. In: Parry ML, Carter TR & Konijn NT (eds.). *The Impact of Climatic Variations on Agriculture*. Vol. I. Assessments in Cool Temperature and Cold Regions. Kluwer Academic Publishers Group, Dordrech, pp. 415-444.

Björnsson H 2004. Mineralisation of nitrogen in relation to climatic variation and soil. In Hatch DJ, Chadwick DR, Jarvis SJ & Roker RA (eds.). *Controlling nitrogen flows and losses,* Wageningen Academic Publishers, The Netherlands, pp. 140-142.

Björnsson H & Helgadóttir Á 1988. The effect of temperature variation on grass yield in Iceland, and us implication for dairy farming. In: Parry ML, Carter TR & Konijn NT (eds.). *The Impact of Climatic Variations on Agriculture*. Vol. I. Assessments in Cool Temperature and Cold Regions. Kluwer Academic Publishers Group, Dordrecht, pp. 445-474.

Bonesmo H 1999. Modelling spring growth of timothy and meadow fescue by an expolinear growth equation. *Acta Agric. Scand., Sect. B*. Soil and plant Sci. 49, 216-224.

Bonesmo H & Bélanger G 2002. Timothy yield and nutritive value by the CATIMO model: I. Growth and nitrogen. *Agron. J*. 94, 337-345.

Bouman BAM, van Keulen H, van Laar HH & Rabbinge R 1996. The 'school of de Wit' crop growth simulation models: A pedigree and historical overview. *Agricultural systems* 52, 171-198.

Box GEP & Jenkins JM 1970. *Time Series Analysis, Forecasting and Control*. Holden-Day, San Francisco. 553 p.

Brynjólfsson R 1994. Áhrif háarsláttar á uppskeru og gæði heyja [Impact of second cut on hay quality]. *Ráðunautafundur 1994,* 206-213. (In Icelandic).

Einarsson M 1972. *Evaporation and potential evapotranspiration in Iceland*. The Icelandic Meteorological Office, Reykjavík, 8 p.

Gustavsson AM, Angus JF & Torssell BWR 1995. An integrated model for growth and nutritional value of timothy. *Agric. Syst*. 47, 73-92.

Payne RW, Baird DB, Gilmour AR, Harding SA, Lane PW, Murray DA, Soutar DM, Thompson R, Todd AD, Tunnicliffe Wilson G, Webster R & Welham SJ 2000. *The guide to GenStat*. Release 4.2. Part 2: Statistics. VSN International Ltd, Oxford. 782 p.

Thorvaldsson G & Björnsson H 1990. The effects of weather on growth, crude protein and digestibility of some grass species in Iceland. *Icelandic Agricultural Sciences* 4, 19-36.

Thorvaldsson G 1992. The effect of temperature on growth, development and nitrogen in shoots and roots in timothy (*Phleum pratense* L.), tested in growth chambers. *Acta Agric. Scand., Sect. B, Soil and Plant Sci.* 42, 158-163.

Thorvaldsson G 1998. The effects of weather on onset of growth in Icelandic grass fields. In: *Crop development for the cool and wet regions of Europe*. COST 814 Workshop. European Commission, Brussels-Luxembourg. pp. 25-31.

Thorvaldsson G, Haahr PT & Høegh K 2000. *Growth, development and nutritional value of grass species and varieties cultivated in Greenland, Iceland and the Faroe Islands 1996-1998*. Rala Report no. 206, 40 p.

Thorvaldsson G & Martin RC 2004. Growth responses of seven perennial grass species to three temperature regimes applied at two growth stages. *Acta Agric. Scand., Sect. B, Soil and Plant Sci.* 54, 14-22.

Torssell BWR, Kornher A & Svensson A 1982. *Optimization of parameters in a yield prediction model for temporary grasslands*. Swedish University of Agricultural Sciences, Department of Plant Husbandry, Report 112. Uppsala, Sweden. 33 p.

Torssell BWR & Kornher A 1983. Validation of a yield production model for temporary grasslands. *Swedish J. Agric. Res.*, 13, 125-135.

Manuscript recieved June 24, 2004
Accepted October 18, 2004