Modelling Grass Growth with LINGRA-N-Plus

Teaching Guide

School of Water, Energy and Environment
December 2020

Abstract

LINGRA-N is a computer model which can simulate grass growth under potential, water-limited and nitrogen-limited growing conditions. The background document and detailed information about LINGRA-N and its FORTRAN code are provided by Wolf (2012b). Under the NERC Research Translation: Grassland Management project (NE/R017387/1), supported by the Sustainable Agriculture Research and Innovation Club (SARIC), the original LINGRA-N model was developed into a Microsoft Excel workbook (LINGRA-N-Plus) for use as an adaptive learning tool by students, grassland managers and advisors. This Teaching Guide describes the background information of the tool and some of the ways in which the model can be used to look at the effect of temperature, carbon dioxide concentration, harvest intervals, nitrogen application and rooting depth.

Contents

Abstract 1
1. Why modelling? 2
2. Background 2
3. Structure of the model 5
4. The Control worksheet 6
 4.1 Climate inputs 7
 4.2 Temperature 10
 4.3 Atmospheric CO_2 concentration 13
 4.4 Harvest interval 14
 4.5 Nitrogen application 16
 4.6 Rooting depth 20
5. Acknowledgements 21
6. References 21
7. Answers 23
 Activity 1 - Temperature 23
 Activity 2 - Atmospheric CO_2 concentration 23
 Activity 3 – Harvest interval 23
 Activity 4 - Nitrogen application 24
 Activity 5 - Rooting depth 24

Burgess PJ[1], Giannitsopoulos ML[1], Richter GM[2], Topp CFE[3], Bell M[4], Takahashi T[5], Ingram J[6] (2020) Modelling Grass Growth with a LINGRA-N-Plus: Teaching Guide. Cranfield University, December 2020.

[1]Cranfield University, Cranfield, Bedfordshire, MK43 0AL
[2]Rothamsted Research, Harpenden, AL5 2JQ
[3]SRUC, Peter Wilson Building, West Mains Rd, Edinburgh, EH9 3JG
[4]The University of Nottingham, Sutton Bonington Campus, Loughborough, LE12 5RD
[5]Rothamsted Research, North Wyke EX20 2SB
[6]Countryside & Community Research Institute, University of Gloucestershire,
P.Burgess@cranfield.ac.uk; M.Giannitsopoulos@cranfield.ac.uk

1. Why modelling?

The Oxford English Dictionary defines a model as "a simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions".

Models are generally developed to make life more predictable, effective, efficient and/or enjoyable. We can use crop growth models for research or to guide decision-making. In terms of training, models can clarify and synthesise our existing knowledge and provide a framework to share knowledge with others.

2. Background

There are a number of grass growth models, which operate on a daily time-step. Unlike annual crop models, grass models must address both tillering and leaf senescence.

One group of grass models is based on the Hurley Pasture Model that was developed near Hurley in Berkshire and is described by Johnson and Thornley (1985) and Thornley (1998). The model assumes four age categories of leaf and shoot and root growth is dependent on levels of carbon and nitrogen substrate. Our experience of using this model is that the predicted growth rates are sensitive to assumed substrate levels. Another grass model is the PGSUS model from New Zealand (Romera et al. 2010).

A major group of grass models is based on LINGRA (Schapendonk et al. 1998). The LINGRA (LINtul GRAss) model was developed in the Netherlands, adapted from the LIght INTerception and UtiLization simulator, which was developed to model potato crop production (Spitters and Schapendonk 1990), applying the principles of sink-source regulation. If for example the source-limited growth is larger than the sink-limited, then the actual growth rate is equal to the sink-limited growth and the surplus assimilates are stored as reserves. The sink-limited growth rate is limited by the potential extension rate of leaves (and stems), which are temperature and water-stress dependent. The source-limited growth rate is determined by the level of photosynthesis and reserve availability.

The calibration of the LINGRA model is described by Bouman et al (1996). The model was also developed for regional grass yield forecasting including the effect of water-limitation and climate change (Rodriguez et al. 1999). It has been used to predict the growth and development of perennial ryegrass across the European Union (JRC MARS 2012) and it was originally programmed in Fortran (Wolf 2012a). Other models to be based on LINGRA include the GrazeGro model used in Northern Ireland (Barrett et al. 2004, 2005), the BASGRA model (van Oijen et al. 2015) and the BeGraS model used by Rothamsted (Qi et al. 2017).

A subsequent version of the model, LINGRA-N was developed to describe the growth and development of perennial ryegrass across the EU under either potential, water-limited or nitrogen (N)-limited growing conditions (Wolf 2012b). LINGRA-N simulates the growth of a grass crop as a function of intercepted radiation, temperature and light use efficiency, while the user has also the option of selecting the desired irrigation and nitrogen application regime. Soil water and simple nitrogen balances are simulated, along with the effects of water and nitrogen supply on crop growth.

In this workshop, we are using LINGRA-N-Plus which is a Microsoft Excel version of a model based on LINGRA-N, which has been developed as part of the NERC Grassland Management translation project involving Cranfield University, Rothamsted Research, SRUC, the University of Nottingham and the University of Gloucestershire.

LINGRA-N-Plus includes five major changes from the LINGRA-N model :

1: The soil nitrogen availability is determined using algorithms described by Addiscott and Whitmore (1987) where nitrogen availability is affected by both temperature and water availability (See Section 4.5).

2: The model assumes that at each harvest the proportion of stem harvested is the same as the proportion of green leaf harvested.

3: A thermal time approach is used to describe the development of the grass from the beginning to the end of the year using the BBCH scale (*Biologische Bundesanstalt, Bundessortenamt and Chemical Industry*; Lancashire et al. 1991). The BBCH scale for grasses is described by Gustavsson (2011) (Table 1). When the grass is harvested, it is assumed that development is reset, with the default setting being the onset of tillering (BBCH 21). The model assumes that the partitioning of dry matter to green leaves, stem, seed, and roots is dependent on the development stage (Table 2). Compared to version 2 of the model, and following a comparison of the model outputs with the grass yields reported by Morrison et al (1980) harvested at an interval of 28 days, a slight variation was made to the partitioning to green leaf and stem between BBCH stages 30 to 60, and the default radiation use efficiency was reduced from 3 g (MJ PAR)$^{-1}$ to 2.5 g (MJ PAR)$^{-1}$.

Table 1. Summary of selected part of the BBCH development stages of forage grasses (after Gustavsson 2011)

BBCH stage	Description
0	Germination
9	Emergence of seedling at soil surface
10-19	Leaf development
21	Beginning of tillering; main shoot and one tiller detectable
30	Beginning of stem elongation
50	First spikelet of the inflorescence is just visible
60	Beginning of flowering
65	Full flowering; half of anthers mature
90	Grain fully ripe

Table 2. Assumed partitioning of dry matter to different components of the grass crop with development stage. Note that the partitioning factors to leaf and stem between BBCH 30 and 65 (indicated in bold) have been slightly modified relative to version 2 of the model.

Development stage	BBCH	Thermal time[a] (°Cd)	Above ground to leaf	Above ground to stem	Above ground to seed	Total DM to roots
Sowing to emergence	0 to 9	60	1	0	0	0.50
Emergence to tillering	9 to 21	155	0.90	0.10	0	0.40
Tillering to stem elongation	21 to 30	150	0.90	0.10	0	0.15
Stem elongation to flowering	30 to 60	400	**0.60**	**0.40**	0	0.15
Flowering to grain filling	60 to 65	100	**0.15**	**0.80**	0.05	0.02
Grain filling to maturity	65 to 90	800	0.05	0.80	0.15	0

[a]: above a base temperature of 3°C

Irving (2015) reports that generally around 80-85% of plant biomass in grasses is partitioned to aboveground organs, such as leaves and stems, and 15–20% is allocated to roots. There are few publications which describe the thermal time values for grass, although Weir et al. (1984) states some values for winter wheat. The assumed sowing to emergence thermal time of 60°Cd (T_{base} = 3°C) is equivalent to Weir et al's value of 148°Cd (T_{base} = 1°C) when the temperature is 4.5°C resulting in 40 days. An emergence to flowering thermal time of 705°Cd (T_{base} = 3°C) is the same as Weir et al's thermal time of 884°Cd (T_{base} = 1°C) when the temperature is 11°C, taking 89 days. A flowering to maturity thermal time of 900°Cd (T_{base} = 3°C) is equivalent to Weir et al's value of 350°Cd (T_{base} = 9°C) when the temperature is 12.8°C, resulting in 92 days.

4: Harvested dead leaves
In version 3, a proportion of the dead leaves have been added to the yield calculations. The values from Wilman et al. (1976), indicate that the proportion of harvested dead leaves relative to the amount of green leaf and stem changes with the harvest interval (HI; units: days). Wilman et al.'s results can be used to show that the proportion of dead leaf = 0.0035 (HI – 21). As we do have data beyond 70 days, it was assumed that the proportion of dead leaf remained constant at 0.1715 of the green leaf + stem value after 70 days. Hence, we added two new columns within the "Calculations" worksheet (column ER: Dry weight of harvestable "dead leaf" and column EW: Total weight of harvested dead leaf) and added a dead leaf value into the total harvested dry matter within the "Control" worksheet (Cell B34: Total weight of harvested "dead leaf").

5: Residual herbage weight after cutting
Use of version 2 of the model with growers indicated an interest in including the residual herbage weight after cutting on the control sheet. Amaral et al., (2012) provide some analysis of the residual values of ryegrass in Brazil grazed to a height of 5 cm. They report that for grass that was originally at 15 cm and then grazed to 5 cm, the leaf lamina mass was 210 kg ha^{-1}, and the leaf to stem ratio was 0.22:1. Hence the weight of the stem would be 954 kg ha^{-1} and the weight of the resulting leaf and stem would be 1164 kg ha^{-1}. As the total post-grazing herbage mass is 1517 kg ha^{-1}, this implies 353 kg ha^{-1} of dead leaf in the residual height. The results also show that for grass that was originally at 25 cm and then grazed to 5 cm (with a substantially higher stocking density), the leaf lamina mass was 175 kg ha^{-1}, and the leaf to stem ratio was 0.34:1. Hence the weight of the stem would be 514 kg ha^{-1}. The weight of the resulting leaf and stem would then be 689 kg ha^{-1}. As the total post-grazing herbage mass is 1696 kg ha^{-1}, this implies 1,007 kg ha^{-1} of dead leaf in the residual height.

If we assume that the LAI after cutting to 4 cm is 0.5, then assuming a specific leaf weight of 0.0025 m^2 kg^{-1}, results in 200 kg ha^{-1}. Assuming an average leaf: stem ratio of 0.285, would result in a stem weight of 700 kg ha^{-1}, and a total green leaf and stem weight of 900 kg ha^{-1}. To this we could add a mean dead leaf weight of 680 kg ha^{-1}, would result in a residual dry mass of around 1600 kg ha^{-1}. Thus, based on the above calculations, in LINGRA-N-Plus, we are adopting a residual grass weight of 1600 kg ha^{-1} which corresponds to a LAI after cutting of 0.5.

Taking into account the above changes, the current Teaching Guide was updated accordingly.

We are currently investigating the possibility of relating the shoot composition to digestibility and the role of nitrogen leaching. We welcome your feedback on what works well with the model and what can be improved.

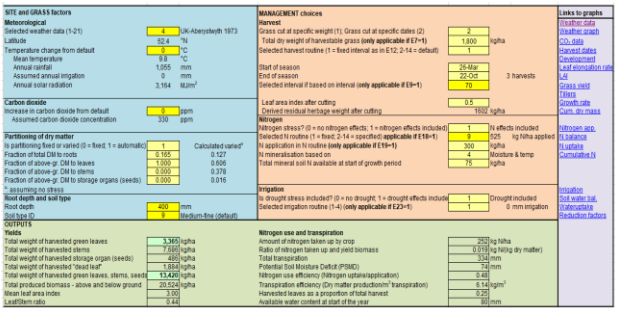
3. Structure of the model

The LINGRA-N-Plus model has been developed as a Microsoft Excel workbook, with a “Control” and one “calculation” worksheet, 20 graphs, and one “weather” and one CO_2 input worksheet (Figure 1).

Action: Review the various components of the worksheet

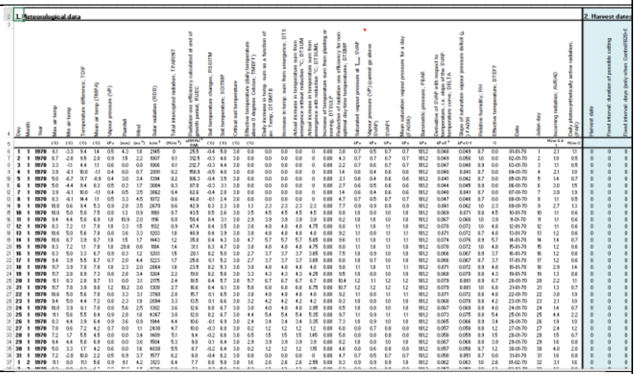
“Control” worksheet

This is the main interface for the user. The user can call in different weather data; modify the temperature, the carbon dioxide concentration, the harvesting and nitrogen regime, the presence or absence of irrigation, and select whether the partitioning percentage is fixed or automatic. If the user chooses fixed partitioning, then he/she also has the option of defining these partitioning factors. The key outputs include the number of harvests, the harvested grass yield and the above-ground biomass production.



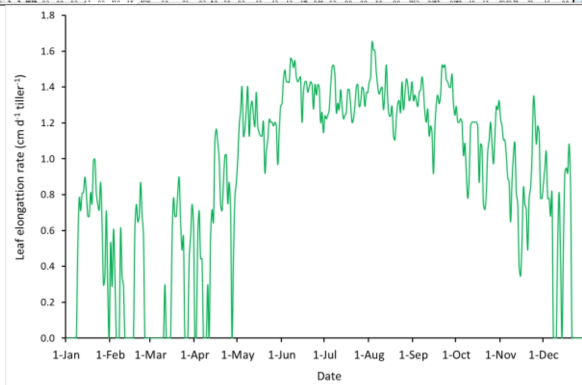
“Calculation” worksheet

This is the engine of the model. Each day in the year (from 1 January to 31 December) appears as a separate line in the worksheet. The same algorithms are used for each day. The worksheet reads in 1) the weather, and calculates 2) harvest dates, 3) crop development, 4) Leaf area-elongation and tillers, 5) biomass production, 6) senescence, 7) partitioning-growth rates, 8) nitrogen, and 9) additional calculations for evapotranspiration



Graphical outputs

Development stage and partitioning, Daily weather, Incoming radiation, Leaf elongation rates and length of leaves, LAI, Grass yield, Cumulative dry mass, Tillers, N uptake, Sink and source growth, Daily and cumulative N uptake, N balance, Cumulative N, Growth rate (sink and source strength), Growth and death rates, Water uptake, Irrigation, Evapotranspiration, Soil water balance, Rooting depth and Reduction factors



Weather data

Within the “Weather_data” worksheet, there are currently available daily weather data for various years and sites (58 records). Some examples include Aberystwyth (1970-1973), Cranfield (2019), Dumfries (2016, 2017, and 2018), North Wyke (2018, 2019), Rothamsted (2009-2014), Sutton Bonington (1984, 1985, 2017, 2018 and 2019), and Haarweg in the Netherlands (1986, 1999).

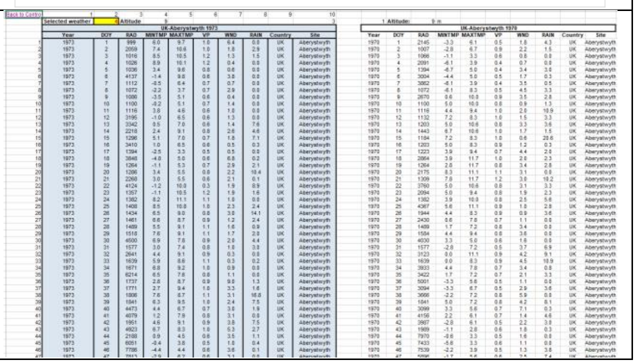
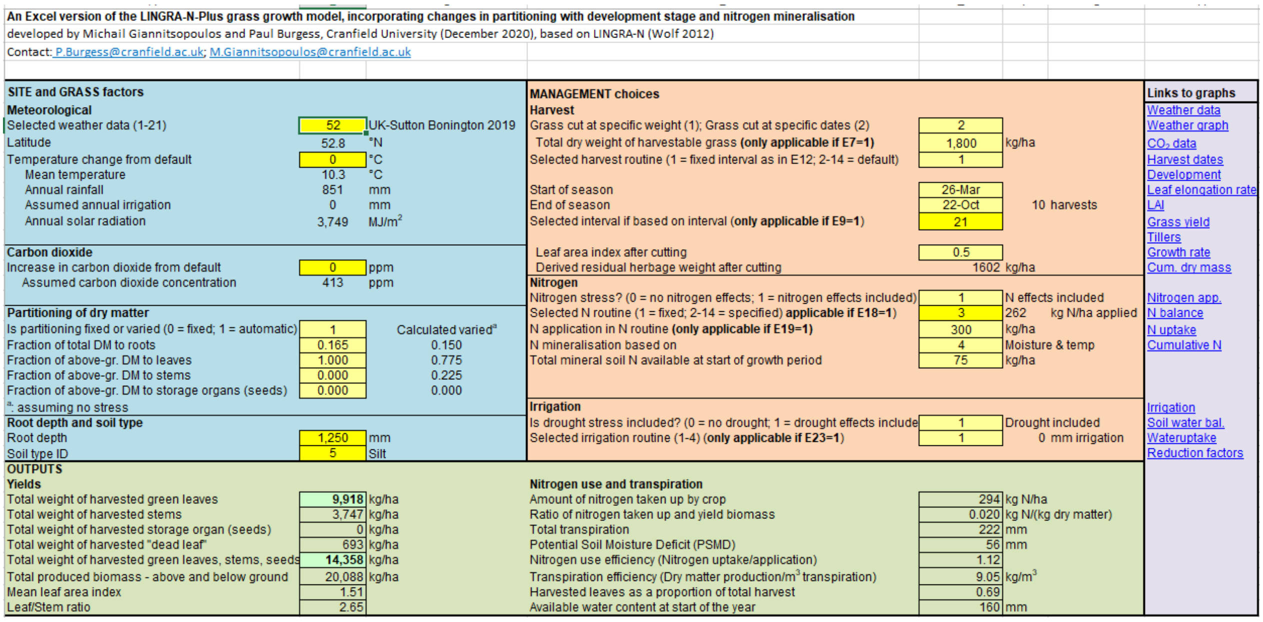


Figure 1. Description and screenshots of the four parts of the LINGRA-N-Plus Workbook

4. The Control worksheet

Question: Can you modify some of the inputs on the Control worksheet?

For this workshop, we will focus on the use of the Control worksheet (Figure 2) to determine the effect of temperature, carbon dioxide concentration, harvest interval, nitrogen, root depth on the yield of green leaf and total dry matter of harvested grass.



An Excel version of the LINGRA-N-Plus grass growth model, incorporating changes in partitioning with development stage and nitrogen mineralisation

developed by Michail Giannitsopoulos and Paul Burgess, Cranfield University (December 2020), based on LINGRA-N (Wolf 2012)

Contact: P.Burgess@cranfield.ac.uk; M.Giannitsopoulos@cranfield.ac.uk

SITE and GRASS factors			
Meteorological			
Selected weather data (1-21)	52	UK-Sutton Bonington 2019	
Latitude	52.8	°N	
Temperature change from default	0	°C	
Mean temperature	10.3	°C	
Annual rainfall	851	mm	
Assumed annual irrigation	0	mm	
Annual solar radiation	3,749	MJ/m^2	
Carbon dioxide			
Increase in carbon dioxide from default	0	ppm	
Assumed carbon dioxide concentration	413	ppm	
Partitioning of dry matter			
Is partitioning fixed or varied (0 = fixed; 1 = automatic)	1		Calculated varied[a]
Fraction of total DM to roots	0.165		0.150
Fraction of above-gr. DM to leaves	1.000		0.775
Fraction of above-gr. DM to stems	0.000		0.225
Fraction of above-gr. DM to storage organs (seeds)	0.000		0.000
[a]: assuming no stress			
Root depth and soil type			
Root depth	1,250	mm	
Soil type ID	5	Silt	

MANAGEMENT choices			
Harvest			
Grass cut at specific weight (1); Grass cut at specific dates (2)	2		
Total dry weight of harvestable grass **(only applicable if E7=1)**	1,800	kg/ha	
Selected harvest routine (1 = fixed interval as in E12; 2-14 = default)	1		
Start of season	26-Mar		
End of season	22-Oct		10 harvests
Selected interval if based on interval (**only applicable if E9=1**)	21		
Leaf area index after cutting	0.5		
Derived residual herbage weight after cutting	1602	kg/ha	
Nitrogen			
Nitrogen stress? (0 = no nitrogen effects; 1 = nitrogen effects included)	1	N effects included	
Selected N routine (1 = fixed; 2-14 = specified) **applicable if E18=1**)	3	262	kg N/ha applied
N application in N routine **(only applicable if E19=1)**	300	kg/ha	
N mineralisation based on	4	Moisture & temp	
Total mineral soil N available at start of growth period	75	kg/ha	
Irrigation			
Is drought stress included? (0 = no drought; 1 = drought effects include	1	Drought included	
Selected irrigation routine (1-4) (**only applicable if E23=1**)	1		0 mm irrigation

Links to graphs
Weather data
Weather graph
CO_2 data
Harvest dates
Development
Leaf elongation rate
LAI
Grass yield
Tillers
Growth rate
Cum. dry mass
Nitrogen app.
N balance
N uptake
Cumulative N
Irrigation
Soil water bal.
Wateruptake
Reduction factors

OUTPUTS		
Yields		
Total weight of harvested green leaves	**9,918**	kg/ha
Total weight of harvested stems	3,747	kg/ha
Total weight of harvested storage organ (seeds)	0	kg/ha
Total weight of harvested "dead leaf"	693	kg/ha
Total weight of harvested green leaves, stems, seeds	**14,358**	kg/ha
Total produced biomass - above and below ground	20,088	kg/ha
Mean leaf area index	1.51	
Leaf/Stem ratio	2.65	

Nitrogen use and transpiration		
Amount of nitrogen taken up by crop	294	kg N/ha
Ratio of nitrogen taken up and yield biomass	0.020	kg N/(kg dry matter)
Total transpiration	222	mm
Potential Soil Moisture Deficit (PSMD)	56	mm
Nitrogen use efficiency (Nitrogen uptake/application)	1.12	
Transpiration efficiency (Dry matter production/m^3 transpiration)	9.05	kg/m^3
Harvested leaves as a proportion of total harvest	0.69	
Available water content at start of the year	160	mm

Figure 2. Screenshot important inputs and important outputs section of the Control worksheet as set for Sutton Bonington 2019

4.1 Climate inputs

Question: Can you select different weather data sets?

Understanding the climate in a given area is an important foundation for understanding crop growth. The Excel model includes predefined set of actual weather records. Daily values of solar radiation, mean air temperature, and rainfall (Figure 3) are three of the driving variables within the LINGRA-N-Plus model (Figure 3). The user can choose selected weather data sets by putting different numbers in cell B7 of the Control worksheet (Table 3)

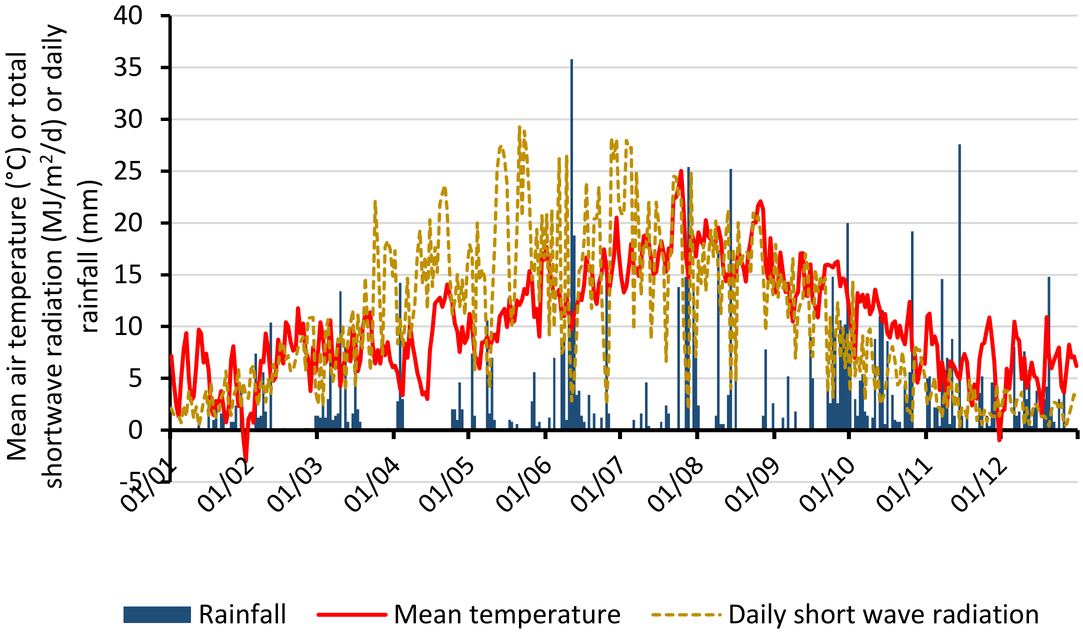


Figure 3. The model is driven by the daily incoming shortwave radiation, the mean air temperature and the rainfall. Daily weather data for Sutton Bonington 2019 are presented.

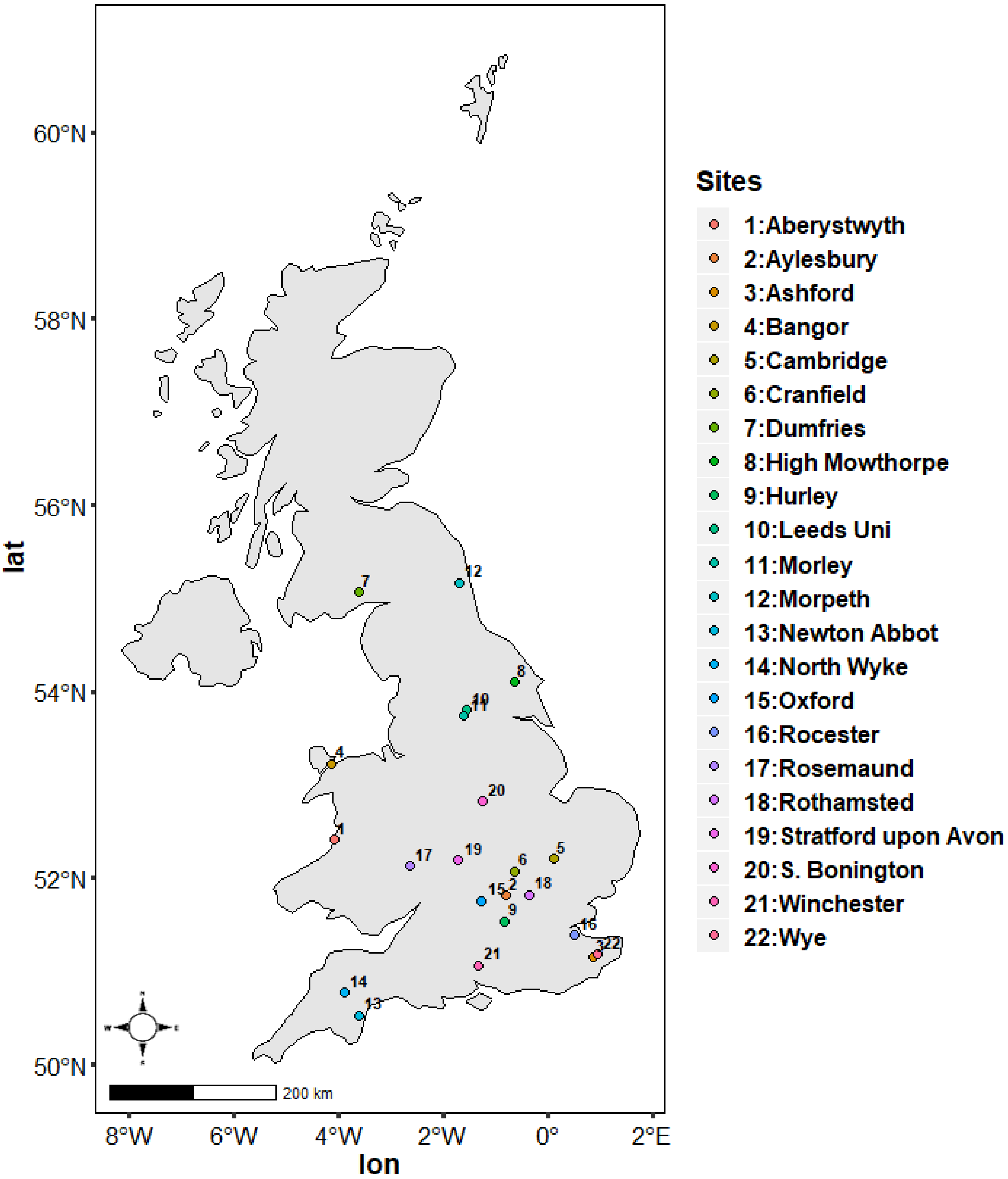


Figure 4. Daily weather data for specific years are available for selected sites in the UK

Table 3. Summary of 52 weather records is provided with three for use in this exercise highlighted

Record (in the model)	Figure 4 number	Country	Selected site	Year	Mean solar radiation (MJ m^{-2} d^{-1})	Mean temperature (°C)	Annual rainfall (mm)
1	1	UK	Aberystwyth	1970	8.1	9.8	1,202
2	1	UK	Aberystwyth	1971	8.9	10.1	950
3	1	UK	Aberystwyth	1972	8.4	9.2	961
4	1	UK	Aberystwyth	1973	8.6	9.8	1,055
5	2	UK	Aylesbury	1973	9.0	9.7	471
6	3	UK	Ashford	1971	9.4	9.6	759
7	3	UK	Ashford	1972	9.0	9.1	717
8	3	UK	Ashford	1973	9.7	9.6	583
9	4	UK	Bangor	1973	8.5	9.9	1,063
10	5	UK	Cambridge	1971	11.2	9.9	542
11	5	UK	Cambridge	1972	8.9	9.6	419
12	5	UK	Cambridge	1973	9.6	9.9	408
13	6	UK	Cranfield	2019	7.5	10.9	487
14	7	UK	Dumfries	2016	8.7	9.8	1,100
15	7	UK	Dumfries	2017	8.7	9.9	1,116
16	7	UK	Dumfries	2018	9.4	9.8	1,162
17	7	UK	High Mowthorpe	1971	7.8	8.4	581
18	7	UK	High Mowthorpe	1972	7.9	7.8	633
19	8	UK	High Mowthorpe	1973	8.1	8.2	613
20	9	UK	Hurley	1971	10.4	9.9	697
21	9	UK	Hurley	1972	9.1	9.5	596
22	9	UK	Hurley	1973	9.0	9.7	548
23	10	UK	Leeds University	1971	7.9	9.3	567
24	10	UK	Leeds University	1972	7.7	8.8	544
25	10	UK	Leeds University	1973	8.9	9.2	505
26	11	UK	Morley	1973	8.9	9.5	621
27	12	UK	Morpeth	1971	7.9	8.6	686
28	12	UK	Morpeth	1972	7.6	8.0	577
29	12	UK	Morpeth	1973	7.9	8.4	522
30	13	UK	Newton Abbot	1971	9.7	10.6	953
31	13	UK	Newton Abbot	1972	9.4	9.9	1,341
32	13	UK	Newton Abbot	1973	9.4	10.4	869
33	14	UK	North Wyke	2018	9.4	10.6	1,064
34	14	UK	North Wyke	2019	10.1	10.4	958
35	15	UK	Oxford	1971	9.1	10.2	741
36	15	UK	Oxford	1972	8.3	9.9	576
37	15	UK	Oxford	1973	9.4	10.2	495
38	16	UK	Rocester	1973	8.6	8.8	775
39	17	UK	Rosemaund	1973	8.8	9.3	516
40	18	UK	Rothamsted	2009	10.3	10.2	765
41	18	UK	Rothamsted	2010	9.8	9.0	644
42	18	UK	Rothamsted	2011	9.9	10.8	571
43	18	UK	Rothamsted	2012	9.5	9.8	1,051
44	18	UK	Rothamsted	2013	9.7	9.5	749
45	18	UK	Rothamsted	2014	10.0	11.2	924
46	19	UK	Stratford	1972	9.5	9.1	593
47	19	UK	Stratford	1973	9.7	9.5	482
48	20	UK	Sutton Bonington	1984	9.1	9.6	648
49	20	UK	Sutton Bonington	1985	8.8	8.8	595
50	20	UK	Sutton Bonington	2017	11.2	10.7	690
51	20	UK	Sutton Bonington	2018	12.2	10.8	545
52	20	UK	Sutton Bonington	2019	10.2	10.3	851

4.2 Temperature

Question: What is the effect of increased temperatures on grass growth?

Theory: the LINGRA-N-Plus model assumes that grass growth is determined either by the capacity of the leaves to absorb assimilates (i.e. sink limitation) or the production of sugars by the leaves (i.e. source limitation). In terms of sink limitation, the model assumes the rate of leaf elongation to be a function of the temperature (Figure 5a). In terms of source resources: the model assumes that there is no photosynthesis until the soil temperature is above 3°C, and that it only reaches a maximum when the soil temperature is above 8°C (Figure 5b). However, the model also assumes that greater leaf production increases the speed with which leaves start to die due to shading, reduced partitioning to leaves, and greater transpiration rates.

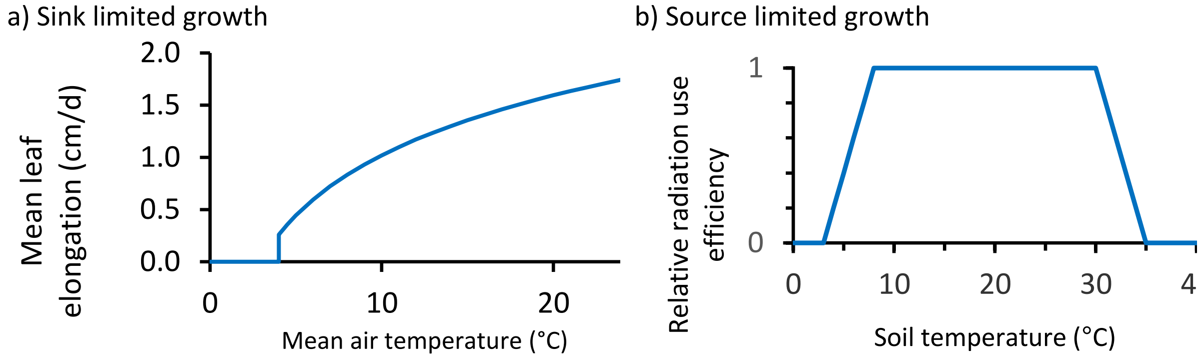


Figure 5. LINGRA-N-Plus assumes that the temperature affects a) rate of leaf elongation and b) the radiation use efficiency. The equation is elongation rate = 0.83*LN (MAX (T_{mean}, 3))-0.8924).

Method: Select Sutton Bonington 2019, record "**52**" in Cell B7, in the Control worksheet (Figure 2). The model reads in the latitude of 52.8°N. Default settings: the choice of the harvest interval can be set by selecting numbers between 2 and 14 in Cell E9 to select a preformatted harvest regime. Select **"1"** in Cell E9 so that the harvest interval is specified by Cell E13. Select a **21-day** interval in Cell E13. The choice of the nitrogen application is determined by Cell E19. If you select **"1"** in Cell E19 then the grass receives a nitrogen application of 30 kg N/ha approximately every three weeks between 1 March and 22 October, providing a total application of 300 kg N/ha. Finally, select the default soil type number **"9"** (Medium-fine) in Cell B28.

Activity 1: Determine the effect of increasing the mean default Sutton Bonington 2019 air temperature by 5°C in Cell B9, on green leaf and total dry biomass. Please fill in the text and Table 4 blanks.

Results: At the Sutton Bonington site, an increase in mean annual temperature from 10.3°C to 15.3 °C assuming a 21-day harvest interval reduces the green leaf yield from ____ to ___ t/ha, and the total dry matter yield increases from ___ t/ha to ___ t/ha (Table 4).

Table 4. Temperature effects on green leaf and total dry biomass assuming a 21-day harvest interval at Sutton Bonington in 2019 (assuming nitrogen levels of 300 kg/ha)

Site	Year	Annual rainfall (mm)	Mean air temperature (°C)	Green leaf yield (t/ha)	Total yield (t/ha)
Sutton Bonington	2019	851	10.3		
			15.3		

Discussion: at temperatures below 20°C, an increase in temperature increases the predicted leaf elongation rate and the radiation use efficiency which will tend to increase yields (Figure 6).

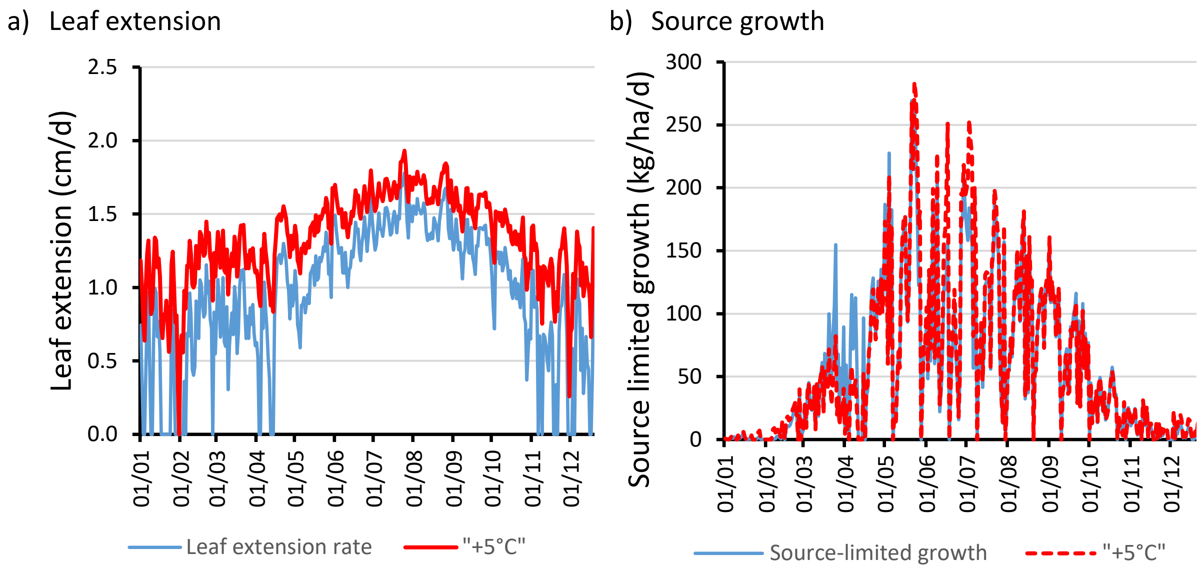


Figure 6. Based on data for Sutton Bonington in 2019, LINGRA-N-Plus shows that an increase in temperature a) increases the leaf extension rate but b) has minimal effect on the level of source-limited growth

The higher temperatures can increase the level of transpiration and therefore the level of water stress. However, the level of drought stress at Sutton Bonington in 2019 was relatively low as the rainfall was relatively evenly distributed (Figure 7).

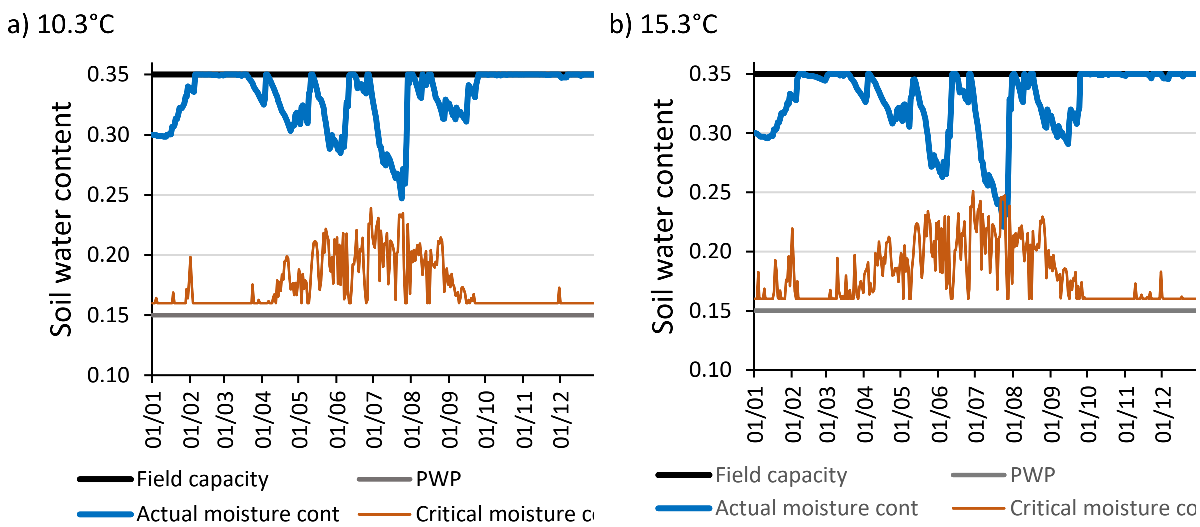


Figure 7. **Drought stress**: data for Sutton Bonington in 2019, LINGRA-N-Plus predicted marginally lower soil water deficits assuming a mean temperature of a) 10.3°C compared to b) 15.3 °C

The main reason for the predicted lower green leaf yield is due to the assumed effect of the increase in temperature accelerating shoot development which leads to relatively less partitioning to green leaf and greater partitioning to stem (Figure 8).

The net effect of these confounding effects for Sutton Bonington was for an increase in temperature to decrease the green leaf yield. However, the total dry matter yield (under well distributed rainfall) was predicted to increase with an increase in temperature.

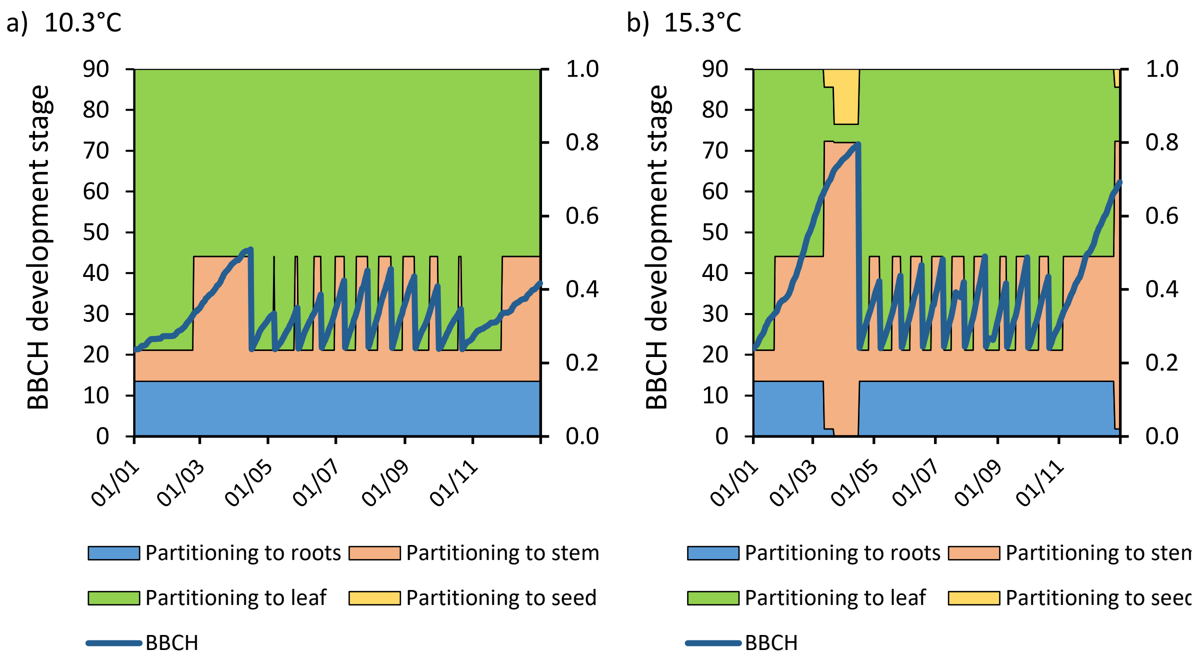


Figure 8. **Dry matter partitioning:** based on data for Sutton Bonington in 2019, the LINGRA-N-Plus shows that an increase in temperature from a) 10.3°C to b) 15.3 °C increases the development rate of the grass which decreases the partitioning to leaf and increases the partitioning to stem

Conclusions

Increasing the temperature affects most of the processes in grass models including an increased turnover rate of green leaf and the faster mineralization of nitrogen (Thornley and Cannell 1997). In their original use of the LINGRA model Schapendonk et al. (1998) at three contrasting sites in North West Spain, the Netherlands, and South West Norway predicted that a 3°C rise in temperature would increase the grass yield by 4-15%, mainly attributed to greater growth in early spring.

Thornley and Cannell (1997) when they used the Hurley Pasture Model predicted that an increase in temperature would decrease leaf longevity and lead to lower leaf area indices, and although higher mineralization would increase nitrogen availability in the short term, in the long-term increased mineralization and volatisation rates eventually reduced nitrogen availability.

4.3 Atmospheric CO_2 concentration

Question: What is the effect on a change in carbon dioxide concentration on grass growth?

Theory: The model assumes that an increased carbon dioxide concentration increases the relative radiation use efficiency (Figure 9), with a 3.4% increase in radiation use efficiency with a 50 ppm increase in carbon dioxide concentration.

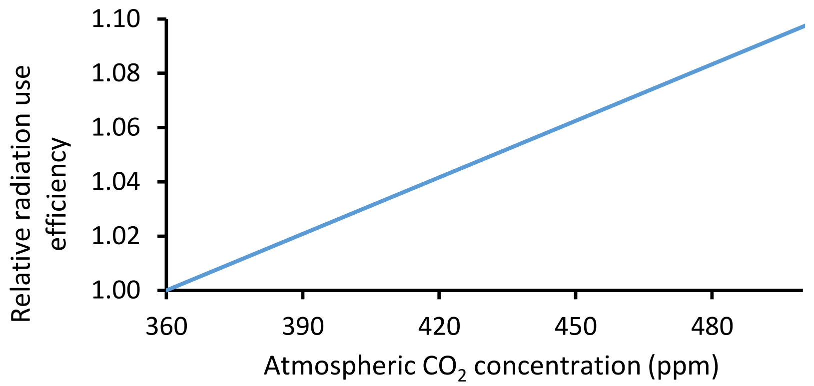


Figure 9. Radiation use efficiency is assumed to increase as the CO_2 concentration increases

Method: Select Sutton Bonington 2019, record **"52"** in Cell B7, in the Control worksheet. As in the previous example, select **"1"** in Cell E9 so that the harvest interval is specified by Cell E13. Select a **21-day** interval in Cell E13. Select the nitrogen application in Cell E19 by selecting **"1"** so that the grass receives 30 kg N/ha approximately every three weeks, providing a total application of 300 kg N/ha, and the default medium-fine soil type (selection **"9"**) in Cell B28.

Activity 2: Determine the effect of increasing the default atmospheric CO_2 concentration at Sutton Bonington 2019, by 50 ppm in Cell B16 on green leaf and total dry biomass. Please fill in the text and Table 5 blanks.

Results: Assuming a harvest interval of 21 days, increasing the CO_2 concentration by 50 ppm, from 413 ppm to 463 ppm, increased the green leaf yield from ____ to ___ t/ha (___%) and the total dry matter yield from ___ to ___ t/ha (___ %) (Table 5).

Table 5. Carbon dioxide effects on green leaf and total dry biomass assuming a 21-day harvest interval at Sutton Bonington in 2019 (assuming nitrogen levels of 300 kg/ha)

Site	Year	Mean air temperature (°C)	Carbon dioxide concentration (ppm)	Green leaf (t/ha)	Total (t/ha)
Sutton Bonington	2019	10.3	413		
			463		

Discussion: The primary effect of increased CO_2 concentrations is to increase the assumed radiation use efficiency, and this leads to higher dry matter yields. However, the extent to which this is achieved is determined by whether the grass yield is primarily source- or sink-limited. Often the predicted growth in LINGRA-N-Plus is sink-limited and hence the yield effect is not as great as that expected from the simple CO_2 response. CO_2 enrichment experiments in Switzerland (Hebeisen et al. 1997) and Portugal (Daepp et al. 2000) have shown an increase in yield of 1.4-3% for a 50 ppm increase in atmospheric CO_2 concentration. Using the LINGRA model, Rodriguez et al. (1999) in Wageningen, showed that 700 ppm of CO_2 shortened the cutting interval to achieve the maximum yield by 15%, compared to a CO_2 of 350 ppm. Hebeisen et al. (1997) reported that the yield response of *L. perenne* to CO_2 depended on the defoliation frequency.

4.4 Harvest interval

Question: What is the effect of different harvest intervals on green leaf and total grass yields?

Theory: The LINGRA-N-Plus model describes both the production of green leaf and the total production of dry matter. The model predicts that an increasing proportion of the dry matter is allocated to stem as the grass develops (Table 2).

Method: in order to determine the effect of harvest interval, we verified the results of LINGRA-N-Plus with the results of a harvest interval experiment carried out in 1973 in Aberystwyth and reported by Wilman et al (1976).

- Hence for this part of the analysis we will select **"4"** in Cell B7 to use the weather data for Aberystwyth in 1973.
- In the experiment described by Wilman et al (1976), they took an initial cut from each plot on 26 March and then recorded the yield of green leaf, stem, and seeds at either interval of 21, 28, 35, 42, 56 or 70 days until 22 October 1973.
- The nitrogen application rate is assumed to be 26 kg N/ha applied every three weeks (i.e. nitrogen option **"3"** in cell E19), a medium-fine soil type (select **"9"** in Cell B28) and **75** kg/ha for the available soil mineral N at start of growth period (Cell E22).

Activity 3: Determine the effect of different harvest intervals on the yield of green leaf and total dry biomass. Please fill in Table 6.

Results: The model predicts that as the harvest interval increases, the yield of green leaf declines (Table 6; Figure 10).

Table 6. Predicted effect of harvest interval on green leaf and total dry biomass for Aberystwyth in 1973 (assuming nitrogen levels of 262 kg/ha)

Yield	Harvest interval (days)									
	2	4	7	14	21	28	35	42	56	70
Green leaf yield										
Total DM yield										

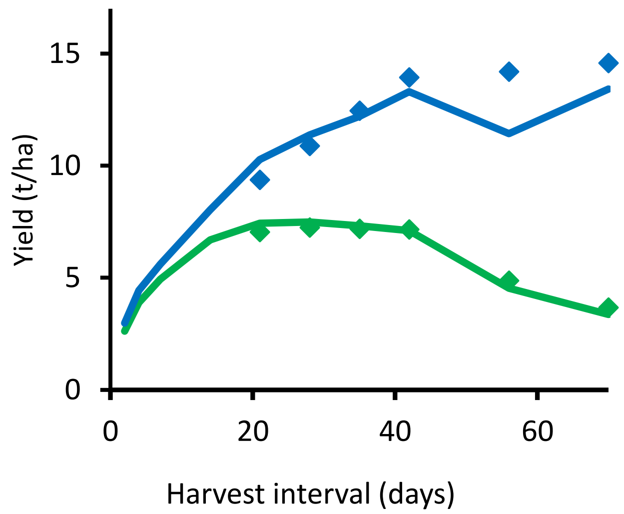


Figure 10. Effect of cutting interval (26 March to 22 October) as predicted by the LINGRA-N-Plus model at 262 kg N/ha. Measured green leaf (◆) and total dry biomass (◆) yields as reported by Wilman et al. (1976).

Discussion: the decline in green leaf yield as the harvest interval increases is a result of two factors. One of the key features of a grass model is the turnover of leaves. Hence as the harvest interval increases a greater proportion of green leaves die before they are harvested as demonstrated by the variation in the grey area between Figure 11a and Figure 11b. The second effect is the increased partitioning to stems.

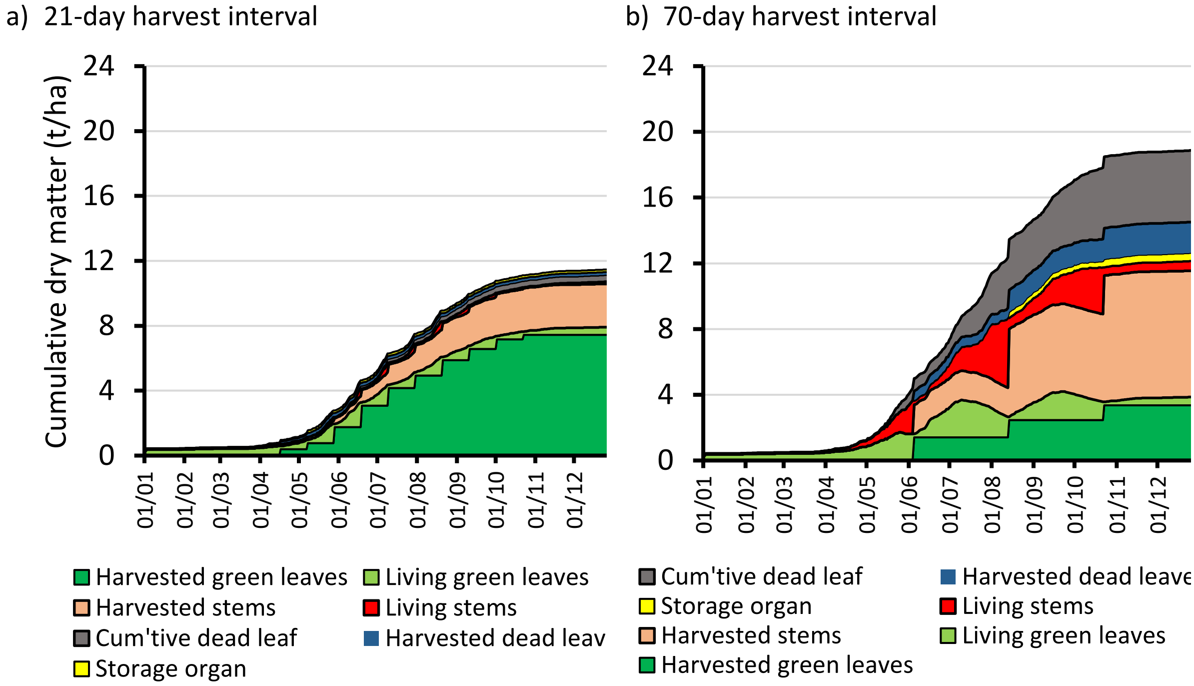


Figure 11. Effect of a harvest interval of a) 21 days and b) 70 days between March and October on the yield components of grass and the cumulative total of dead green leaf

By contrast, the total yield increases because the model assumes that stems do not decay but remain harvestable. The outputs from the model match those of Wilman et al. 1976 (Figure 10 and Figure 12). Binnie et al. (1972) in a 1967 Irish experiment, also showed that increasing the interval between cuts to 10-weekly, increased the yield of dry biomass.

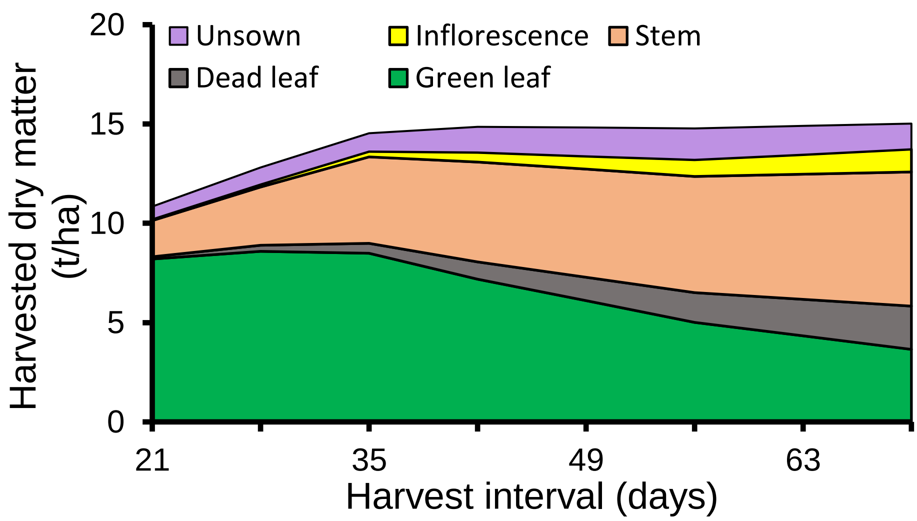


Figure 12. **Measured** effect of harvest interval on the components of total grass yield (Wilman et al. 1976)

4.5 Nitrogen application

Question: What is the effect of nitrogen application on green leaf and total grass yields?

Theory: The LINGRA-N-Plus model describes the response of grass to soil nitrogen primarily by using the nitrogen routine developed for LINGRA-N. The model maintains a nitrogen balance which describes the nitrogen in the soil, and the nitrogen in the crop.

Availability of nitrogen

In the original LINGRA-N model it was assumed that a proportion of decomposable nitrogen compounds became available each day. By contrast the LINGRA-N-Plus model includes four nitrogen sources: slowly decomposable (N_{rpm}) and fast and easily decomposable organic compounds (N_{dpm}), the total mineral N available at start of growth period (N_{mins}) and nitrogen application as fertilizers (Table 7). The model assumes that 70% of the applied fertilised nitrogen is available for recovery from the soil (Control sheet, cell C103); hence an application of 200 kg N means that 140 kg N is available.

Table 7. Assumed nitrogen sources in LINGRA-N-Plus

Sources of nitrogen	Abbreviation	Amount	Unit
Slowly decomposable compounds	N_{rpm}	150	kg N/ha
Fast and easily decomposable organic compounds	N_{dpm}	50	kg N/ha
Total mineral soil N available at start of growth period	N_{mins}	75	kg N/ha
Nitrogen applied as fertilizer on particular dates		262	kg N/ha

The assumption in LINGRA-N-Plus is that the net mineralization of organic nitrogen (N_{min}) is calculated by the first order kinetics using the two pools of mineralisable nitrogen N_{dpm} and N_{rpm}.

$$N_{min} = N_{rpm}\,[1 - \exp(-k_{rpm}(T))_t] + N_{dpm}\,[1 - \exp(-k_{dpm}(T))_t] \quad \text{Equation 1}$$

The rate constants in Equation 1 can be determined from the soil temperature (T) and a moisture content factor $(\theta - \theta_{PWP})/\theta_{FC}$, according to the Arrhenius relationship (Equation 2, 3; Kersebaum 1995; Addiscott and Whitmore 1987).

$$k_{rpm}(T) = 4.0 \times 10^9 \times \exp\left(-\frac{8400}{T + 273}\right) \times \frac{(\theta - \theta_{PWP})}{\theta_{FC}} \quad \text{Equation 2}$$

$$k_{rpm}(T) = 5.6 \times 10^{12} \times \exp\left(-\frac{9800}{T + 273}\right) \times \frac{(\theta - \theta_{PWP})}{\theta_{FC}} \quad \text{Equation 3}$$

Uptake of nitrogen

The model assumes that the daily uptake of nitrogen by the crop (Column JK in the Calculation sheet) is the minimum of either the nitrogen availability in the soil (as described above) or the nitrogen demand of the crop. The nitrogen demand of the crop ($N_{d\ crop}$) is then calculated as the sum of the nitrogen demand of the leaves, stems, and roots minus the nitrogen recirculated from dying leaves (Equation 4).

$$N_{d\ crop} = N_{d\ leaf} + N_{d\ stem} + N_{d\ root} - N_{recirculated\ dead\ leaf} \quad \text{Equation 4}$$

The N demand of the leaves is the product of the weight of leaves and the maximum nitrogen concentration of the leaf minus the actual nitrogen content of the leaf (Equation 5)

$$N_{demand\ of\ leaf} = (W_{leaf}\ N_{\max\ \_leaf}) - N_{leaf} \quad \text{Equation 5}$$

The model calculates a mean nitrogen concentration for the leaves, stems, and roots. The effect of nitrogen on grass growth is then dependent on a calculated nitrogen nutrition index NNI (Column KH in the Calculations worksheet; Equation 6).

$$NNI = \frac{N_{conc-aboveground} - N_{conc-residual}}{N_{conc-optimum} - N_{conc-residual}} \quad \text{Equation 6}$$

The $N_{conc-optimum}$ for the leaves is set as 0.0350 kg N/kg DM (Cell C134 in the Control worksheet), with the value for the stem set as 0.5 times that of the leaves (Cell C137). The residual N fraction in the leaves is set as 0.01 kg N/kg dry biomass in Cell C141, and the residual N fraction in the stem is set as 0.005 kg N/kg dry biomass in cell C142. The value of NNI determines the relative rate of tiller formation (Columns DB and DC) and the leaf death rate due to N shortage (Column IM).

Method: Use the same meteorological data for Aberystwyth as described for the last exercise. Calculate the effect of three nitrogen application rates (cell E19), of 0 kg N/ha (Option **"2"**), 262 kg N/ha (Option **"3"**) and 525 kg N/ha (Option **"9"**) on the green leaf and total dry matter yield of grass harvested at intervals of 2, 4, 7, 14, 21, 28, 35. 42, 56 and 70 days (by altering Cell E13).

Activity 4: Determine the effect of three N applications (0, 262, 525 kg N/ha) on the yield of green leaf and total dry biomass. Please fill in the text and Table 8 blanks.

Results: The LINGRA-N-Plus model predicted that at a harvest interval of 21 days (i.e. 10 harvests between 26 March and 22 October), the total dry biomass yield increases from ___ t/ha with 0 kg N/ha, to ___ t/ha at 262 kg N/ha, and ___ t/ha at 525 kg N/ha (Table 8). The LINGRA-N-Plus model predicts a similar profile to the measured green leaf and total dry biomass yields of the Aberystwyth experiment reported by Wilman et al. (1976) (

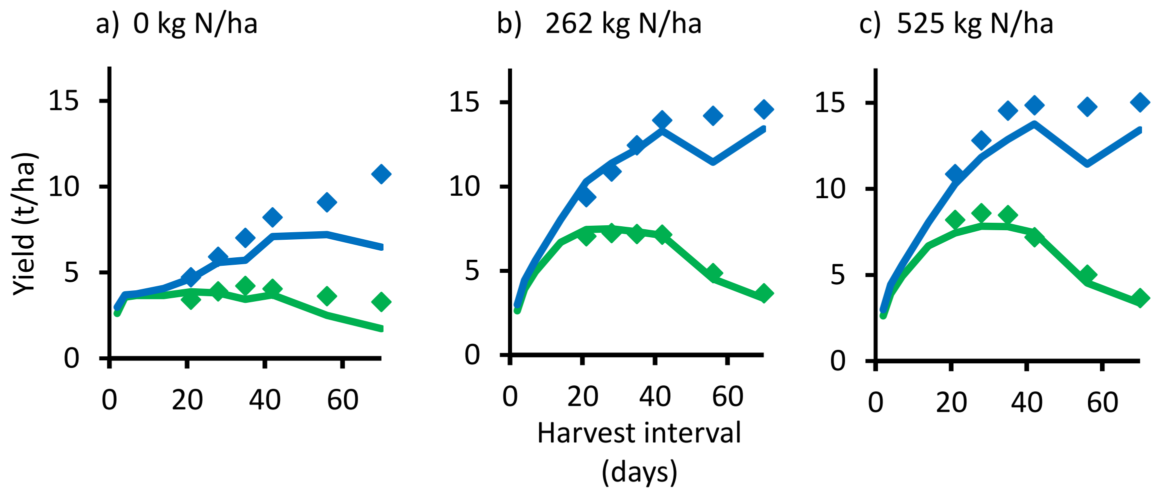


Figure 13). (Note that the predicted lower than measured yield with 56 days is related to the last harvest taking place on 11 September; the treatment resulted in three harvests which is the same as with a 70-day interval).

Table 8. Effect of harvest interval (Mar-Oct) on the green leaf and total dry biomass yields at Aberystwyth as a) measured by Wilman et al (1976) and b) predicted by the LINGRA-N-Plus model

Nitrogen		Harvest interval (days)									
(kg N/ha)		2	4	7	14	21	28	35	42	56	70
a) Measured											
0	Green leaf					3.41	3.91	4.23	4.06	3.64	3.29
	Total					4.73	5.92	7.03	8.22	9.1	10.73
262	Green leaf					7.04	7.23	7.18	7.15	4.86	3.66
	Total					9.36	10.88	12.45	13.93	14.19	14.57
525	Green leaf					8.2	8.59	8.49	7.19	5.01	3.65
	Total					10.85	12.81	14.54	14.86	14.77	15.02

b) Modelled	
0	Green leaf
	Total
262	Green leaf
	Total
525	Green leaf
	Total

The model also shows the depletion of organic nitrogen from the beginning of the year (N_{rpm} plus N_{dpm}), and the uptake of nitrogen by the crop in the purple area (Figure 14).

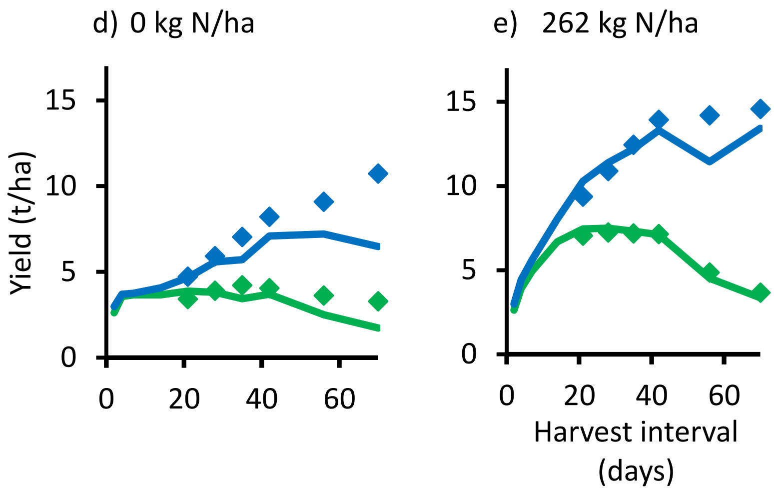


Figure 13. Effect of cutting interval (March to October) at a) 0 kg N/ha, b) 262 kg N/ha, and c) 525 kg N/ha as predicted by LINGRA-N-Plus at 262 kg N/ha. Measured green leaf (◆) and total dry biomass (◆) yields as reported by Wilman et al. (1976).

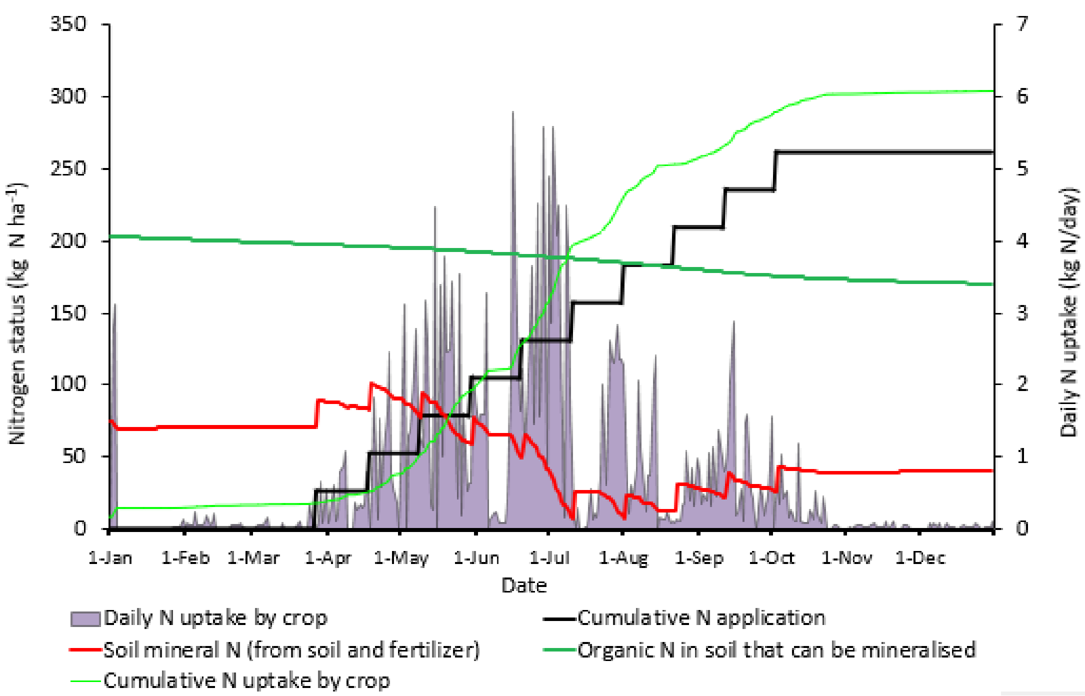


Figure 14. Calculated soil and crop nitrogen assuming the application of 262 kg N (at equal amounts of 26.2 kg/ha/day) on ten dates between 26 March and 22 October

Discussion: Modelling the nitrogen uptake and responses of crops in models is relatively rare. However, it proved possible to use LINGRA-N-Plus to describe the nitrogen responses of grass to a range of harvest intervals as described by Wilman et al. (1976). In order to obtain a yield of up to 10 t dry matter/ha at the zero-nitrogen application it was necessary to assume that the amount of nitrogen available at the beginning of the season was 75 kg N/ha. The experiment described by Wilman et al (1976) was in a recently cultivated field so the nitrogen content may have been high. Morrison et al. (1980) in a comparison of 21 grassland experimental sites in England and Wales below an altitude of 366 m between 1970 and 1974, calculated a mean contribution of N from the soil of 60 kg ha^{-1}.

4.6 Rooting depth

Question: What is the effect of rooting depth on green leaf and total grass yields?

Theory: The soil moisture content within the root zone is calculated as the product of the soil water content (θ_v; mm/mm) and the root depth ($Root_{depth}$). The soil moisture content on a specific day i ($Root_{depth} \cdot \theta_v$) is equal to the soil water content on the preceding day plus any precipitation (*P*) and irrigation (*I*), minus any evaporation (*E*), transpiration (*Tr*), and drainage (*D*) (Equation 7).

$$Root_{depth} \cdot \theta v_i = Root_{depth} \cdot \theta v_{i-1} + P + I - E - Tr - D \qquad \text{Equation 7}$$

The value of θ_v affects the relative transpiration rate of the crop (Column MR), if the actual root water content is below a critical value, dependent on the water content at permanent wilting point (θ_{PWP}) (Equation 8)

$$\frac{Tr_{actual}}{Tr_{potential}} = \frac{(\theta_{actual} - \theta_{PWP})}{(\theta_{critical} - \theta_{PWP})} \qquad \text{Equation 8}$$

The relative transpiration rate in turn determines the transpiration rate of the crop (Column NV), the radiation use efficiency which determines the source-limited growth rate (Column GU), the root growth rate (Column CY), and actual death rate of the leaves (RDR_{leaf}) (Column FU).

Method: The crop rooting depth can be modified in Cell B27 of the Control worksheet. The default root depth is 400 mm. What is the effect of the increasing the default rooting depth to 1,000 mm? The effect of rooting depth can be compared for three sites: Aberystwyth 1973 with an annual rainfall of 1,055 mm, Sutton Bonington 2019 with a rainfall of 858 mm, and Rothamsted 2011 with a rainfall of 571 mm.

Activity 5: What is the effect of increasing rooting depth from 400 mm to 1,000 mm, on the yield of green leaf and total dry biomass for Aberystwyth 1973, Sutton Bonington 2019 and Rothamsted 2011? Please fill in the text and Table 9 blanks.

Results: The results show that the effect of increasing the rooting depth at the relative wet sites at Aberystwyth 1973 and Sutton Bonington 2019 was minimal. However, at the dry site of Rothamsted, increasing the rooting depth from 400 to 1000 mm increases the green leaf yield from ___ to ___ t/ha and the total dry matter yield from ___ to ___ t/ha.

Table 9. Effect of rooting depth at three sites on the green leaf and total yield of grass harvested at an interval of 21 days and with nitrogen application of 300 kg N/ha (cell E19=1).

Record in the model	Site	Year	Annual rainfall (mm)	Rooting depth (mm)	Green leaf (t/ha)	Total (t/ha)
4	Aberystwyth	1973	1,055	400		
				1000		
35	Sutton Bonington	2019	851	400		
				1000		
26	Rothamsted	2011	571	400		
				1000		

Discussion: Lee et al. (2019) in a growth chamber experiment in UK, emphasized that future forage grass productivity and plant water content are likely to decline under summer droughts.

5. Acknowledgements

We are thankful for the support received from NERC (NE/R017387/1) and the Sustainable Agriculture Research Innovation Club.

6. References

Addiscott TM, Whitmore AP (1987) Computer simulation of changes in soil mineral nitrogen and crop nitrogen during autumn, winter and spring. Journal of Agricultural Science, Cambridge 109, 141–157. http://dx.doi.org/10.1017/s0021859600081089.

Amaral MF, Mezzalira JC, Bremm C, Da Trindade JK, Gibb MJ, Sune RWM, de F Carvalho PC (2012). Sward structure management for a maximum short-term intake rate in annual ryegrass. Grass and Forage Science, 68, 271–277 http://dx.doi.org/10.1111/j.1365-2494.2012.00898.x

Barrett PD, Laidlaw AS, Mayne CS (2004) An evaluation of selected perennial ryegrass growth models for development and integration into a pasture management decision support system. Journal of Agricultural Science 142, 327–334.

Barrett PD, Laidlaw AS, Mayne CS (2005) GrazeGro: a European herbage growth model to predict pasture production in perennial ryegrass swards for decision support. European Journal of Agronomy 23, 37–56.

Binnie RC, Harrington FJ (1972) The effect of cutting height and cutting frequency on the productivity of an Italian ryegrass sward. Grass and Forage Science, 27, 177–182. http://dx.doi.org/10.1111/j.1365-2494.1972.tb00706.x.

Bouman BAM, Schapendonk AHCM, Stol W, van Kraalingen DWG (1996) Description of the Growth Model LINGRA as implemented in CGMS. Quantitative Approaches in Systems Analysis No. 7. https://models.pps.wur.nl/system/files/LINGRA.pdf

Daepp M, Suter D, Almeida JPF, Isopp H, Hartwig UA, Frehner M, Blum H, Nosberger J, Luscher A (2000) Yield response of *Lolium perenne* swards to free air CO_2 enrichment increased over six years in a high N input system on fertile soil. Global Change Biology 6, 805-816.

Gustavsson AM (2011) A developmental scale for perennial forage grasses based on the decimal code framework. Grass and Forage Science 66, 93–108.

Giannitsopoulos ML, Burgess PJ, Bell, MJ, Richter GM, Topp CFE, Ingram J, Takahashi T (2020). Grass production simulation models: LINGRA as an interactive learning tool. *Under Review* in Environmental Modelling and Software.

Hebeisen T, Luscher A, Zanetti S, Fischer BU, Hartwig UA, Frehner M, Hendrey GR, Blum H, Nosberger J (1997) Growth response of *Trifolium repens* L and *Lolium perenne* L as monocultures and bi-species mixture to free air CO_2 enrichment and management. Global Change and Biology 3, 149-160.

Irving LJ (2015) Carbon assimilation, biomass partitioning and productivity in grasses. Agriculture 5, 1116-1134; doi:10.3390/agriculture5041116

Johnson IR, Thornley JHM (1985). Dynamic model of the response of a vegetative grass crop to light, temperature and nitrogen. Plant, Cell and Environment 8: 485-499.

JRC MARS (2012) The Lingra Model. Accessed 25 February 2019. https://marswiki.jrc.ec.europa.eu/agri4castwiki/index.php/The_Lingra_model

Kersebaum KC (1995) Application of a simple management model to simulate water and nitrogen dynamics. Ecological Modelling 81, 145–156. http://dx.doi.org/10.1016/0304-3800(94)00167-g

Lancashire PD, Bleiholder H, Boom T, van den Langeluddeke P, Stauss R, Weber E, Witzenberger A (1991) A uniform decimal code for growth stages of crops and weeds. Annals of Applied Biology, 119, 561–601.

Lee MA, Howard-Andrews V, Chester M (2019) Resistance of multiple diploid and tetraploid perennial ryegrass (*Lolium perenne* L.) varieties to three projected drought scenarios for the UK in 2080. Agronomy, 9 http://dx.doi.org/10.3390/agronomy9030159.

Morrison J, Jackson MV, Sparrow PE (1980) The Response of Perennial Ryegrass to Fertilizer Nitrogen in relation to Climate and Soil. Report of the joint ADAS/GRI Grassland Manuring Trial – GM 20. Technical report No 27. February 1980. Grassland research Institute, ADAS and Rothamsted Experimental Station.

Qi A, Murray P, Richter GM (2017) Modelling productivity and resource use efficiency for grassland ecosystems in the UK. European Journal of Agronomy 89, 148-158.

Rodriguez D, van Oijen M, Schapendonk AHMC (1999) LINGRA-CC: a sink-source model to simulate the impact of climate change and management on grassland productivity. New Phytologist 144, 359-368.

Romera AJ, Beukes P, Clark C, Clark D, Levy H, Tait A (2010) Use of a pasture growth model to estimate herbage mass at a paddock scale and assist management on dairy farms. Comp and Elec in Agric 74: 66–72.

Schapendonk AHCM, Stol W, van Kraalingen DWG, Bouman BAM (1998) LINGRA, a sink/source model to simulate grassland productivity in Europe. European Journal of Agronomy 9, 87-100.

Spitters CJT, Schapendonk AHCM (1990) Evaluation of breeding strategies for drought tolerance in potato by means of crop growth simulation. Plant and Soil 123, 193-203.

Thornley JHM (1998) Grassland Dynamics: An Ecosystem Simulation Model. CAB International.

Thornley JHM, Cannell MGR (1997). Temperate grassland responses to climate change: an analysis using the Hurley Pasture Model. Annals of Botany 80, 205-221.

van Oijen M, Höglind M, Cameron DR, Thorsen SM (2015) BASGRA_2014 (Version 1.0). Zenodo. http://doi.org/10.5281/zenodo.27867

Weir AH, Bragg PL, Porter JR, Rayner JH (1984) A winter wheat crop simulation model without water or nutrient limitations. Journal of Agricultural Science Cambridge 102: 371-382.

Wilman D, Droushiotis D, Koocheki A, Lwoga AB, Shim JS (1976) The effect of interval between harvests and nitrogen application on the digestibility and digestible yield and nitrogen content and yield of four ryegrass varieties in the first harvest year. The Journal of Agricultural Science, Cambridge 86, 393–399.

Wolf J (2012a). LINGRA model a simple grass model for potential and water limited conditions. Accessed 25 February 2019. https://models.pps.wur.nl/lingra-model-simple-grass-model-potential-and-water-limited-conditions

Wolf J (2012b). LINGRA-N: Simple generic model for simulation of grass growth under potential, water limited and N limited conditions. https://models.pps.wur.nl/lingra-n-grassland-model-potential-water-limited-and-n-limited-conditions-fortran

7. Answers

Activity 1 - Temperature

Results: At the Sutton Bonington site, an increase in mean annual temperature from 10.3°C to 15.3°C assuming a 21-day harvest interval reduces the green leaf yield from 9.04 to 8.94 t/ha, whereas the total dry matter yield increases from 12.43 t/ha to 13.45 t/ha (Table A1).

Table A1. Temperature effects on green leaf and total grass dry biomass assuming a 21-day harvest interval at Sutton Bonington in 2019 (assuming nitrogen levels of 300 kg/ha)

Site	Year	Annual rainfall (mm)	Mean air temperature (°C)	Green leaf yield (t/ha)	Total yield (t/ha)
Sutton Bonington	2019	851	10.3	9.04	12.43
			15.3	8.94	13.45

Activity 2 - Atmospheric CO_2 concentration

Results: Assuming a harvest interval of 21 days, increasing the CO_2 concentration from 413 to 463 ppm, increased the green leaf yield from 9.04 to 9.22 t/ha (+1.9%) and the total dry matter yield from 12.43 to 12.71 t/ha (2.2%) (Table A2).

Table A2. Carbon dioxide effects on green leaf and total yields assuming a 21-day harvest interval at Sutton Bonington in 2019 (assuming nitrogen levels of 300 kg/ha)

Site	Year	Mean air temperature (°C)	Carbon dioxide concentration (ppm)	Green leaf (t/ha)	Total (t/ha)
Sutton Bonington	2019	10.5	413	9.04	12.43
			463	9.22	12.71

Activity 3 – Harvest interval

Results: The model predicts that as the harvest interval increases, the yield of green leaf declines and the total dry matter yield plateaus (Table A3).

Table A3. Predicted effect of harvest interval on green leaf and total dry biomass for Aberystwyth in 1973 (assuming nitrogen levels of 262 kg/ha)

Yield	Harvest interval (days)									
	2	4	7	14	21	28	35	42	56	70
Green leaf (t/ha)	2.62	3.90	4.93	6.69	7.43	7.49	7.32	7.11	4.53	3.36
Total DM (t/ha)	2.98	4.43	5.60	8.04	10.27	11.38	12.20	13.30	11.43	13.42

Activity 4 - Nitrogen application

Results: LINGRA-N-Plus predicts that at a harvest interval of 21 days (i.e. 10 harvests between 26 March and 22 October), the total dry biomass yield increases from 5.35 t/ha with 0 kg N/ha, to 10.27 t/ha at 262 kg N/ha, and at 525 kg N/ha (Table A4). The LINGRA-N-Plus model predicts a similar profile to the measured green leaf and total dry biomass yields of the Aberystwyth experiment reported by Wilman et al. (1976) (

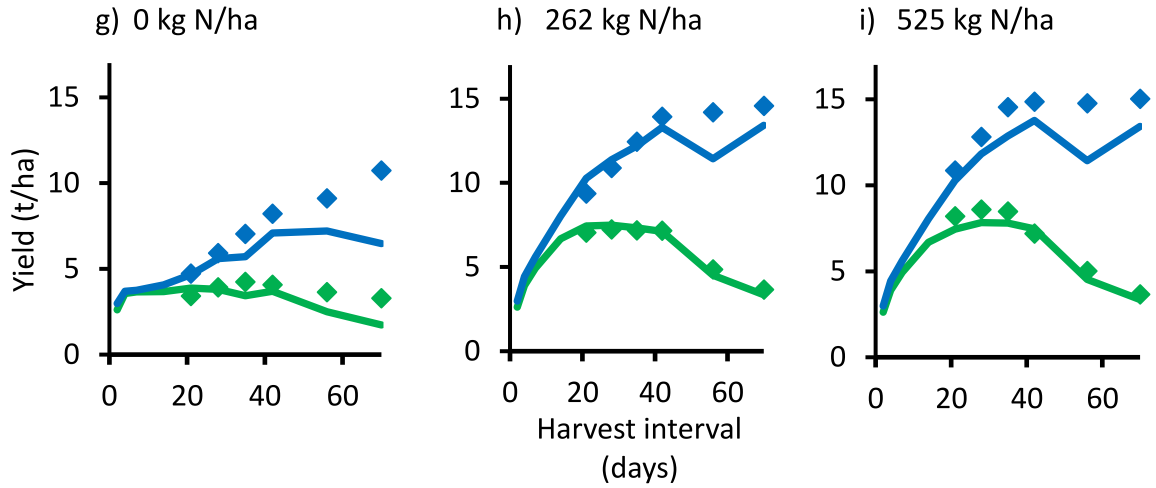


Figure 12). (Note that the predicted lower than measured yield with 56 days is related to the last harvest taking place on 11 September; the treatment resulted in three harvest which is the same as with a 70-day interval).

Table A4. Effect of harvest interval (Mar-Oct) on the green leaf and total dry biomass yields (t/ha) at Aberystwyth as a) measured by Wilman et al (1976) and b) predicted by LINGRA-N-Plus

Nitrogen (kg N/ha)		Harvest interval (days) 2	4	7	14	21	28	35	42	56	70
c) Measured											
0	Green leaf					3.41	3.91	4.23	4.06	3.64	3.29
	Total					4.73	5.92	7.03	8.22	9.1	10.73
262	Green leaf					7.04	7.23	7.18	7.15	4.86	3.66
	Total					9.36	10.88	12.45	13.93	14.19	14.57
525	Green leaf					8.2	8.59	8.49	7.19	5.01	3.65
	Total					10.85	12.81	14.54	14.86	14.77	15.02
d) Modelled											
0	Green leaf	2.62	3.57	3.66	3.67	3.88	3.81	3.43	3.69	2.50	1.73
	Total	2.98	4.07	4.22	4.44	**5.35**	6.02	6.00	7.50	6.80	6.72
262	Green leaf	2.62	3.90	4.93	6.69	7.44	7.49	7.32	7.11	4.52	3.36
	Total	2.98	4.43	5.60	8.04	**10.28**	11.38	12.20	13.30	11.43	13.42
525	Green leaf	2.62	3.90	4.93	6.69	7.44	7.83	7.81	7.46	4.53	3.36
	Total	2.98	4.43	5.60	8.04	**10.28**	11.83	12.87	13.77	11.44	13.42

Activity 5 - Rooting depth

Results: The results show that the effect of increasing the rooting depth at the relative wet sites at Aberystwyth 1973 and Sutton Bonington 2019 was minimal. However, at the dry site of Rothamsted, increasing the rooting depth from 400 to 1,000 mm increases the green leaf yield from 8.79 to 10.30 t/ha and the total dry matter yield from 13.21 to 15.32 t/ha (Table A5).

Table A5. Effect of rooting depth at three sites on the green leaf and total yield of grass harvested at an interval of 21 days and with nitrogen application of 300 kg N/ha (cell E19=1).

Code	Site	Year	Annual solar radiation (MJ m^{-2})	Annual rainfall (mm)	Rooting depth (mm)	Green leaf (t/ha)	Total (t/ha)
4	Aberystwyth	1973	3164	1,055	400	7.44	10.28
					1,000	7.44	10.28
52	Sutton Bonington	2019	3749	851	400	11.00	15.80
					1,000	11.06	15.89
26	Rothamsted	2011	3643	571	400	8.79	13.21
					1,000	10.30	15.32