Modelling Grass Growth with a LINGRA-N Tool
Teaching Guide

School of Water, Energy and Environment
April 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 an Microsoft Excel workbook (the LINGRA-N tool) 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.

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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 a LINGRA-N tool which is a Microsoft Excel version of 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.

The LINGRA-N tool includes three important changes from the LINGRA-N model.
1: The soil nitrogen availability is determined using an algorithms described by Addiscott and Whitmore (1987) where nitrogen availability is affected by both temperature and water availability.

2: The model assumes that the stem contributes to photosynthesis and the leaf area index.

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). 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.

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

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	1.00	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	0.50	0.50	0	0.15
Flowering to grain filling	60 to 65	100	0.20	0.75	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

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

Daily weather data for 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) are included.

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

	A	B	C	D	E	F	G	H
1	**An Excel version of the LINGRA-N grass growth model, incorporating changes in partitioning with development stage and nitrogen mineralisation**							
2	developed by Michail Giannitsopoulos and Paul Burgess, Cranfield University (February 2020), based on LINGRA-N (Wolf 2012)							
3	Contact: P.Burgess@cranfield.ac.uk; M.Giannitsopoulos@cranfield.ac.uk							
4								
5	**SITE and GRASS factors**			**MANAGEMENT choices**				**Links to graphs**
6	**Meteorological**			**Harvest**				
7	Selected weather data (1-21)	21	UK-Sutton Bonington 2019	Grass cut at specific weight (1); Grass cut at specific dates (2)	2			Weather data
8	Latitude	52	°N	Total dry weight of harvestable grass **(only applicable if E7=1)**	1,800	kg/ha		Weather graph
9	Temperature change from default	0	°C	Selected harvest routine (1 = fixed interval as in E12; 2-8 = default)	1			
10	Mean temperature	10.3	°C	Start of season	01-Mar			Leaf elongation rate
11	Annual rainfall	851	mm	End of season	22-Oct			Growth rate
12	Assumed annual irrigation	0	mm	Selected interval if based on interval (**only applicable if E9=1**)	21		11 harvests	
13	Annual solar radiation	3,749	MJ/m^2	Residual grass determined by weight (1) or LAI (2)	2			
14				Residial weight after cutting **(only applicable if E13 = 1)**	1,500	kg/ha		
15	**Carbon dioxide**			Leaf area index after cutting **(only applicable if E13 = 2)**	0.5			
16	Increase in carbon dioxide from default	0	ppm					
17	Assumed carbon dioxide concentration	413	ppm	**Nitrogen**				
18				Nitrogen stress? (0 = no nitrogen effects; 1 = nitrogen effects included)	1	N effects included		
19	**Partitioning of dry matter**			Selected N routine (1 = fixed; 2-14 = specified) **applicable if E18=1)**	1	300	kg N/ha applied	CO_2 data
20	Is partitioning fixed or varied (0 = fixed; 1 = automatic)	1	Calculated varied[a]	N application in N routine **(only applicable if E19=1)**	300	kg/ha		Reduction factors
21	Fraction of total DM to roots	0.165	0.150	N mineralisation based on	4	Moisture & temp		
22	Fraction of above-gr. DM to leaves	1.000	0.760	Total mineral soil N available at start of growth period	75	kg/ha		
23	Fraction of above-gr. DM to stems	0.000	0.240					LAI
24	Fraction of above-gr. DM to storage organs (seeds)	0.000	0.000					Grass yield
25	[a]: assuming no stress			**Irrigation**				Cum. dry mass
26	**Root depth**			Is drought stress included? (0 = no drought; 1 = drought effects include	1	Drought included		Tillers
27		400	mm	Selected irrigation routine (1-4) **(only applicable if E23=1)**	1	0 mm irrigation		
28								
29	**OUTPUTS**							N balance
30	**Yields**			**Nitrogen use and transpiration**				N uptake
31	Total weight of harvested green leaves	**11,643**	kg/ha	Amount of nitrogen taken up by crop	335	kg N/ha		Cumulative N
32	Total weight of harvested stems	5,435	kg/ha	Ratio of nitrogen taken up and yield biomass	0.020	kg N/(kg dry matter)		Soil water bal.
33	Total weight of harvested storage organ (seeds)	0	kg/ha	Total transpiration	238	mm		Wateruptake
34	Total weight of harvested green leaves, stems, & see	**17,078**	kg/ha	Nitrogen use efficiency (Nitrogen uptake/application)	1.12			Irrigation
35	Total produced biomass - above and below ground	23,960	kg/ha	Transpiration efficiency (Dry matter production/m^3 transpiration)	10.08	kg/m^3		
36	Mean leaf area index	1.43		Harvested leaves as a proportion of total harvest	0.68			Development
37								

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 model (Figure 5). The user can choose selected weather data sets by putting different numbers in cell B7 of the Control worksheet (Figure 4; 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 24 weather record are provided with three for use in this exercise highlighted

Record (in the model)	Country	Selected site	Year	Mean solar radiation (MJ m^{-2} d^{-1})	Mean temperature (°C)	Annual rainfall (mm)
1	UK	Aberystwyth	1970	8.1	9.8	1,202
2	UK	Aberystwyth	1971	8.9	10.1	950
3	UK	Aberystwyth	1972	8.4	9.2	961
4	UK	Aberystwyth	1973	8.6	9.8	1,055
5	UK	Cranfield	2019	7.5	10.9	487
6	UK	Dumfries	2016	8.7	9.8	1,100
7	UK	Dumfries	2017	8.7	9.9	1,116
8	UK	Dumfries	2018	9.4	9.8	1,162
9	UK	North Wyke	2018[a]	9.4	10.6	1,064
10	UK	North Wyke	2019	10.0	10.4	958
11	UK	Rothamsted	2009	10.3	10.2	765
12	UK	Rothamsted	2010	9.8	9.0	644
13	UK	Rothamsted	2011	9.9	10.8	571
14	UK	Rothamsted	2012	9.5	9.8	1,051
15	UK	Rothamsted	2013	9.7	9.5	749
16	UK	Rothamsted	2014	10.0	11.2	924
17	UK	Sutton Bonington	1984	9.1	9.6	648
18	UK	Sutton Bonington	1985	8.8	8.8	595
19	UK	Sutton Bonington	2017	11.2	10.7	690
20	UK	Sutton Bonington	2018	12.2	10.8	545
21	UK	Sutton Bonington	2019	10.2	10.3	851
22	Netherlands	Haarweg	1986	9.4	8.8	759
23	Netherlands	Haarweg	1999	10.3	10.6	697

4.2 Temperature

Theory: the LINGRA-N tool 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 tool 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 "**21**" in Cell B7, in the Control worksheet (Figure 2). Assume the latitude is 52°N. Default settings: the choice of the harvest interval can be set by selecting numbers between 2 and 8 in Cell E9 to select a preformatted harvest regime. Select **"1"** in Cell E9 so that the harvest interval is specified by Cell E12. Select a **21-day** interval in Cell E12. 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 March and October, providing a total application of 300 kg N/ha.

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 ___ °C to ___ °C assuming a 21 day harvest interval reduces the green leaf yield from ___ to ___ t/ha, whereas 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				

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 tool shows that an increase in temperature a) increases the leaf extension rate and b) the level of source-limited growth, particularly in January and February

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 tool 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 tool shows that an increase in temperature from a) 10.4°C to b) 15.4 °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 Carbon dioxide

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 carbon dioxide concentration increases

Method: Select Sutton Bonington 2019, record **"21"** 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 E12. Select a **21-day** interval in Cell E12. Select the nitrogen application in Cell E19 by selecting **"1"** so that the grass receives a nitrogen application of 30 kg N/ha approximately every three weeks, providing a total application of 300 kg N/ha.

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 from ___ to ___ 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				

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 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

Theory: The LINGRA-N tool 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 have validated the results of LINGRA-N tool 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 intervals 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).

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).

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	58	70
Green leaf yield										
Total DM yield										

Figure 10. Effect of cutting interval (26 March to 22 October) as predicted by the LINGRA-N tool 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

Theory: The LINGRA-N tool 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 tool 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 tool

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 tool 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}.

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

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).

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

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

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).

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

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)

$$N_{demand\,of\,leaf} = (W_{leaf}\,N_{\max_leaf}) - N_{leaf} \qquad \text{Equation 5}$$

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).

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

The $N_{conc\text{-}optimum}$ 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"**), 226 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 E12).

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 tool 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; Figure 13). The LINGRA-N Tool 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 harvest 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 tool

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
226	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										
226	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) 226 kg N/ha, and c) 525 kg N/ha as predicted by the LINGRA-N tool model 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 2 October

Discussion: Modelling the nitrogen uptake and responses of crops in models is relatively rare. However, it proved possible to use the LINGRA-N tool 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

Theory: the LINGRA-N tool calculates the soil moisture content (θv; mm/mm) within the root zone as the product of the soil water content and the root depth ($Root_{depth}$). The soil moisture content on the daily basis where the soil water content on day i ($Root_{depth}$. θv) 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).

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

The value of θv affects the relative transpiration rate of the crop (Column MO), 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 (Column NT) in turn determines the transpiration rate of the crop (Column MO), the radiation use efficiency which determines the source-limited growth rate (Column GR), the root growth rate (Column CX), and death rate of the leaves (RDR_{leaf}) (Column FR) with Equation 9,

$$RDR_{leaf} = \left(1 - \frac{Tr_{actual}}{T_{rpotential}}\right) \qquad \text{Equation 9}$$

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 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 1,000 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).

Code	Site	Year	Annual rainfall (mm)	Rooting depth (mm)	Green leaf (t/ha)	Total (t/ha)
4	Aberystwyth	1973	1,055			
21	Sutton Bonington	2019	851			
13	Rothamsted	2011	571			

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.

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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 11.72 to 10.55 t/ha, whereas the total dry matter yield increases from 17.85 t/ha to 20.75 t/ha (Table 4).

Table 4. 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	11.72	17.85
			15.3	10.55	20.75

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 11.72 to 11.87 t/ha (+1.2%) and the total dry matter yield from 17.85 to 18.12 t/ha (+1.5%) (Table 5).

Table 5. 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	11.72	17.85
			463	11.87	18.12

Activity 3 - Harvest

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

Table 10. 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	58	70
Green leaf yield	3.18	4.77	6.19	8.22	8.69	7.68	7.69	7.15	4.19	3.44
Total DM yield	3.59	5.41	7.02	10.04	12.92	12.79	14.13	14.87	13.22	15.83

Activity 4 - Nitrogen application

Results: The LINGRA-N tool 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 5.53 t/ha with 0 kg N/ha, to 12.92 t/ha at 262 kg N/ha, and 13.87 t/ha at 525 kg N/ha (Table 8; Figure 13). The LINGRA-N Tool 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 harvest which is the same as with a 70-day interval).

Table 11. 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 tool

Nitrogen		Harvest interval (days)									
(kg N/ha)		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
226	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	3.18	3.74	3.77	3.98	3.79	3.71	4.06	3.94	2.40	1.90
	Total	3.60	4.28	4.38	4.93	**5.53**	6.21	7.78	9.07	7.69	11.19
226	Green leaf	3.18	4.78	6.20	8.25	8.69	7.68	7.69	7.15	4.16	3.44
	Total	3.60	5.41	7.02	10.07	**12.92**	12.79	14.13	14.87	12.45	15.83
525	Green leaf	3.18	4.78	6.20	8.79	9.37	9.35	8.91	8.31	4.77	3.53
	Total	3.60	5.41	7.02	10.74	**13.87**	15.21	15.85	16.58	13.58	16.01

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 9.03 to 11.06 t/ha and the total dry matter yield from 14.74 to 17.56 t/ha.

Table 12. 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 rainfall (mm)	Rooting depth (mm)	Green leaf (t/ha)	Total (t/ha)
4	Aberystwyth	1973	1,055	400	8.69	12.92
				1,000	8.75	13.00
21	Sutton Bonington	2019	851	400	10.96	16.72
				1,000	11.05	16.87
13	Rothamsted	2011	571	400	9.03	14.74
				1,000	11.06	17.56