Simulation of grass sward dry matter yield in Slovenia using the LINGRA-N model

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Abstract

Calibration and validation of the LINGRA-N model were performed using herbage dry matter (DM) yield data from field studies conducted at three locations in Slovenia. Calibration was done by minimising root mean square error (*RMSE*) and validation by using *RMSE* and Willmott's index of agreement (d_w). Calibration of LINGRA-N was not successful for the experiment conducted on permanent grassland in Ljubljana in the period 1974-1993 ($RMSE_{\%} = 14\%, d_w = 0.37$). Better results were obtained for grass monocultures in Jablje (J) and Rakičan (R) in the period 1998–2013, with the best fit for cocksfoot (*Dactylis glomerata* L.; $RMSE_{\%} = 12\%, d_w = 0.84$). Fifty-year simulations were performed for cocksfoot (J-DG) and timothy grass (*Phleum pratense* L.) in Jablje (J-PP) and perennial ryegrass (*Lolium perenne* L.) in Jablje (J-LP) and Rakičan. Outliers with very low simulated herbage DM yield were detected only in the second half of the study period and were associated with drought and/or high maximum air temperatures. A time series analysis of annual potential yield values showed a statistically significant ($P=0.05$) negative trend for J-LP (–24 kg DM ha^{-1}year^{-1}) and J-PP (–29 kg DM ha^{-1}year^{-1}). A change in the variability of the reduction factor for crop growth due to drought was already noticeable.

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See online Appendix for additional material.

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Introduction

Grasslands in Slovenia, as in a major part of Europe, are important for forage production and ecosystem preservation, with their value increasing. Productivity, sustainability and nutritive value are of great importance to forage supply production, soil and water protection, natural environment preservation and carbon storing. In the European Union, climate and economic risks vary quite strongly from one Member State to another; so knowing local conditions is fundamental (Žalud *et al*., 2006; Gallego *et al*., 2007). In Slovenia, the area of sown grasslands is increasing and the area of permanent grasslands is not changing (SURS - database output, 2014). The prevalent types in sown grasslands are quality grasses and legumes, which are selected for their higher yield, higher nutritional value, resilience and resistance to diseases and stress (MAFF, 2008). The use of suitable varieties adapted to growth conditions, with high good-quality yields, which are resistant to as many diseases and pests as possible, is one of the greatest challenges in crop production. Experimental fields are thus very important and the data gained from experiments provide a good basis for modelling growth and yield in various weather or climatic conditions.

It is especially notable with grass swards that climatic conditions have a major impact on productivity (Herrmann *et al*., 2005). Weather instability and unpredictability must be taken into account when planning forage production (JRC, 2008). Many analyses have shown the dependence of grass sward productivity on the combination of soil moisture, global irradiation, air temperatures, added nitrogen and mowing or pasture (Riedo *et al*., 1997; Barrett *et al*., 2005; Trnka *et al*., 2006). Laidlaw (2009) highlighted the importance of the precipitation amount for grass sward yield during the vegetation period; however, the distribution of precipitation within the vegetation period is even more important, especially in combination with high air temperatures. Knowledge of responses of various grass monocultures to drought and other weather conditions will be one of the essential prerequisites in professional forage planning and production in the future, when further global warming is expected.

Cocksfoot is very common in Slovenia. Although according to the Agricultural Institute of Slovenia (Verbič, personal source, 2014), summer droughts slow down its growth, and it stays green and keeps growing. Perennial ryegrass grows fast and produces high yields in favourable conditions but its combination of shallow roots and a relatively low temperature ceiling makes it drought and high temperature sensitive. In such conditions, its growth is quickly terminated and, especially with older leys, it can easily happen that the ryegrass dies due to drought and does not recover in autumn. Timothy grass also has a shallow root system and, as such, is drought and high temperature sensitive. However, it does not die as quickly as perennial ryegrass but rather stays dormant until its luxuriant regrowth if conditions are better in autumn (Verbič, personal source, 2014).

A considerable number of models dealing with various agronomical and ecological aspects of grassland have been developed in past decades (Herrmann *et al*., 2005), such as GrazeGro (Barrett and Laidlaw, 2005; Barrett *et al*., 2005), Hurley Pasture (Thornley and Cannell, 1997) PaSim (Riedo *et al*., 1997), STICS (Brisson *et al*., 2003), GEM (Hunt *et al*., 1991), GraS (Siehoff *et al*., 2011), LINGRA (Schapendonk *et al*., 1998) and LINGRA-N (Wolf, 2012). They are used to study the interaction between a number of variables and their impact on grass sward yield and can help in understanding them (Bonesmo and Belanger, 2002; Kajfež-Bogataj, 2005; Angulo *et al*., 2013). The development and use of crop models is very useful when preparing field studies, testing hypotheses and raising new questions (Wolf and Van Ittersum, 2009). Simulations can be performed using archive data or future scenarios (Barrett and Laidlaw, 2005) and are necessary to understand climate change and its impact on vegetation, including crop response (Rapacz *et al*., 2014). Despite many advantages, no model has yet been used in Slovenia because not many researchers have focused on crop modelling in the past.

For small and medium enterprises, which are very common in Slovenia, the stability of forage production is one of the main focal points with regard to grasslands and forage. Since only experiments on grasslands have so far been conducted in Slovenia, modelling seems strategically important in researching new possibilities, planning forage supply and adapting grass swards in the country to changing weather conditions.

The long-term objective of our research was to develop a tool for simulating and evaluating the growth and herbage yield of sown or permanent grasslands that is sensitive to climatic variation, soil properties and management practices (Pogačar *et al*., 2015). It was expected that, after calibration, a major part of inter-annual variability of herbage dry matter (DM) yield could be explained by the model, which would then be available for long-term simulations of grass sward growth and yield. Due to the fact that droughts were the main factor for reduced grass sward yields in the past (Sušnik and Pogačar, 2010), the identification and analysis of drought years were of special interest to us. It would be of great importance, for example, to upgrade the field cultivar experiments of the Agricultural Institute of Slovenia with daily and yearly results of the calibrated model simulations, which would provide much additional data for potential users. Futhermore, grass growth and yield could be simulated using climate change scenarios to contribute to the climate change adaptation plan for Slovene farmers.

Materials and methods

LINGRA-N model

More complex models usually need various sets of input data, which are difficult to obtain. It therefore requires some caution in choosing a model that meets expectations about output and, at the same time, overcomes limitations about the availability of input data. The availability of grass sward yield data is not very good. Long datasets on yield are rare, so many studies use shorter sets from experiments that were not conducted for this purpose (Žalud *et al*., 2006). Reliable and sufficiently long datasets are necessary for model calibration and validation, so the lack of long datasets limits the use of crop models (Trnka *et al*., 2006).

There are many dynamic models for simulating the growth and yield of grass sward but not many of them simulate growth after defoliation (Jing *et al*., 2012). One of these is the LINGRA model (Schapendonk *et al*., 1998), which is based on the sink and source approach. It is a simple model even regarding input data (Bonesmo and Belanger, 2002). The original version of LINGRA was developed for prediction of the productivity of *Lolium perenne* grasslands, with simulated key processes being light utilisation, leaf formation, leaf elongation, tillering, and carbon partitioning to storage, shoots and roots (Rodriguez *et al*., 1999). However, we used the next version, the LINGRA-N model (Wolf, 2012), a generic model that can be used for various grass types growing under a large range of soil and weather conditions with various management regimes. This model was chosen due to the availability of all the necessary input data and especially because the WOFOST model from the same family of models has already been successfully used for maize yield simulations in Slovenia (Ceglar and Kajfež Bogataj, 2012). Soil water (with free drainage) and simple nitrogen balances are simulated, as are the effects of water and nitrogen supply on crop growth. The model can calculate grass growth and yields under potential (*i.e*. optimal), water limited (*i.e*. rain-fed) and nitrogen limited growing conditions (Wolf, 2012). There have been previous reports on LINGRA parameter assessments and intervals for calibration (Bonesmo and Belanger, 2002; JRC, 2004; Van Oijen *et al*., 2005), as well as on testing and validation of the model (Trnka *et al*., 2006; Duru *et al*., 2009). For explanations of the model, see Wolf (2012), JRC (2004), Schapendonk *et al*. (1998) and Bouman *et al*. (1996). The variables and connections that are most important for our research are described in Pogačar and Kajfež Bogataj (2015). The model assumes optimal management of grass sward (Wolf, 2012). Diseases, pests and weeds are not simulated, on the assumption that their influence is much smaller than the influence of abiotic environmental factors (Höglind *et al*., 2001). The routine for irrigation was not used, since there was no irrigation in the experiments and because this is not a common practice in Slovenia. The model does not need phenological stages as an input, temperature sums for reaching them being used instead.

Calibration and validation of the model

Models have to be calibrated before testing on locations for which they were not developed (Merot *et al*., 2008). Wolf (2006) recommends at least a 10-year dataset to calibrate LINGRA. After a simple sensitivity analysis without taking into account interactions, some parameters were excluded from the process; their values are presented in Table 1. The remaining 26 parameters and mowing dates were calibrated separately for each field experiment. The calibration was done by minimising root mean square error (*RMSE*) of the simulated in relation to observed herbage DM yield (likewise Schapendonk *et al*., 1998; Bonesmo and Belanger, 2002; Van Oijen *et al*., 2005; Angulo *et al*., 2013; Jego *et al*., 2013). Datasets on herbage DM yields from three locations were split into two parts: odd years were used for calibration and even years for validation of the model (see *Field data* chapter).

The calibration range for each parameter was obtained from the literature. Where this was not possible, a 30-percent interval around the default model value was used. Mowing dates were also calibrated in order to obtain the most representative values because the model does not provide an option to set mowing dates for each year separately but instead uses the same value for the whole simulation period. Phyton interface was developed to run the model searching for the parameter combination with the lowest *RMSE*: firstly in four groups of simultaneously changing parameters (Table 2; around 40,000 iterations for each group), then in six groups (parameters changing in smaller steps; Table 3, steps 5-10) and finally in two more groups, depending on previous results

(Table 3, steps 11-12). The first ten steps are common to all field experiments, while the last two are field specific. Calibrated parameters and the results of calibration are presented in Table 4.

Instead of the commonly used Pearson's correlation coefficient (r) and determination coefficient (r^2), it is better for validation of the model's simulations to calculate difference measures that seem to contain insightful information (Willmott, 1982). On the basis of this recommendation, *RMSE* (Eq. 1) and Willmott's index d_w (Eq. 2) were used to validate the simulations (see Willmott, 1982; Jego *et al*., 2013; Pogačar *et al*., 2015):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2}, \qquad RMSE_{\%} = \frac{RMSE}{\overline{O}} \times 100, \tag{1}$$

where n is the number of measurements, $\overline{O_i}$ measured values, the average of measured values and P_i simulated values, with excellent results at $RMSE_{\%}$<10% and good at 10%≤$RMSE_{\%}$<20%.

$$d_w = 1 - \frac{\sum_{i=1}^{n}(Pi - Oi)^2}{\sum_{i=1}^{n}(|P_i'| + |O_i'|)^2}, \tag{2}$$

where n, P_i and O_i are defined as in Eq. 1. P_i*'* and O_i*'* are calculated as $P_i - \overline{O}$ and $O_i - \overline{O}$. Willmott's index d_w is notably used to compare model results; its range being from 0 to 1, where 1 means total agreement (Willmott, 1982). For more details on the calibration and validation see Pogačar *et al*. (2015).

Simulations and statistical analysis

The calibrated LINGRA-N model (Figure 1) was used for simulation of herbage DM yield and growth analysis in the 50-year period 1964-2013. Since the calibration was not successful for all experiments (see *Results*), the simulations were done for four cases. Calibrated parameters (Table 4) were used for initialisation of crop data; soil, meteorological and management data are presented in the *Field data* chapter. Each year, the initial soil moisture was set to field capacity, which is considered to be a good approximation for winter or early spring start of simulations (Schapendonk *et al*., 1998; Lazzarotto *et al*., 2009; Jego *et al*., 2013). The simulation is done in each case for the whole period continuously; results are yearly and daily values of output variables.

Table 1. Left: Default parameter values in the LINGRA-N model that have little impact and were not calibrated. Right: Default parameter values that are defined according to the author's instructions.

Parameter (unit)	Default value	Parameter (unit)	Default value
RTMINS (day^{-1})	0.025	IMOPT	2
RDRSHM (day^{-1})	0.03	IDSL	0
RRI (cm day^{-1})	1.2	DVSI	0
RDRNS (-)	0.05	TBASE	0
NLUE (-)	1.1	DVSDLT	1
NSLA (-)	0.5	CFET	1
RNFRT (kg N kg^{-1}SS)	0.005	DEPNR	3.5
COTB (ppm; -)	360; 1 and 720; 1.25	SMDRY (cm^3 cm^{-3})	0.07
RDRLTB (°C; day^{-1})	*	CRAICR (cm^3 cm^{-3})	0.05
KSUB (cm day^{-1})	30 (Jablje)/40 (Rakičan)	CFEV	2

RTMINS, fraction of soil organic N coming available per day; RDRSHM, maximum relative death rate due to shading; , maximum daily increase in rooting depth; RDRNS, maximum relative death rate of leaves due to N stress; NLUE, coefficient for the reduction of RUE due to N stress; NSLA, coefficient for the effect of N stress on specific leaf area reduction; RNFRT, residual N concentration in roots; COTB, correction factor of RUE as a function of atmospheric CO2 concentration; RDRLTB, relative death rate of leaves as dependent on mean daily temperature; KSUB, maximum percolation rate from lower zone to deeper soil layers; IMOPT, switch that determines cutting regime (mowing with IMOPT=2 if MOWDAY is true); IDSL=0, development from emergence/growth start depends on temperature; DVSI, initial development stage; TBASE, lower threshold temperature for leaf area index increase; DVSDLT, development stage above which death of leaves starts; CFET, crop-specific correction for transpiration; DEPNR, crop group number for soil water depletion; SMDRY, soil mositure content at air dry (pF=6.0); CRAICR, critical soil air content for aeration; CFEV, correction factor of time course of soil evaporation. *TMPA: –10, 10, 15, 30, 50; RDRL: 0, 0.01, 0.02, 0.05, 0.09.

Table 2. Steps (1-4) of the model calibration procedure. Names are explained under Table 4.

Step 1	Step 2	Step 3	Step 4
SOITMI	RUNFR	SLA	TDWI
NMINS	NRFTAB	LAICR	KDIF
MNDAT	CLAI	RDMCR	RDRL
DTSMTB	TSUM1	RDI	WREI
RUETB	TMNFTB	LRNR	FRNX
TMPFTB	RDDTB	RNFLV	NMXLV
TILLI	FRTB		
	TMBAS1		

Table 3. Further steps (5-12) of the model calibration procedure, the last two steps are specific for J-DG. Names are explained under Table 4.

Step 5	Step 6	Step 7	Step 8	Step 9	Step 10	Step 11	Step 12
SOITMI	NMINS	MNDAT	DTSMTB	RUETB	TMPFTB	SOITMI	TMBAS1
RUNFR	NRFTAB	CLAI	TSUM1	TMNFTB	TILLI	RUNFR	LAICR
SLA	LAICR	RDMCR	LRNR	RNFLV	RDDTB	NMINS	WREI
TDWI	WREI	RDI	KDIF	RDRL	NMXLV	NRFTAB	FRTB
TMBAS1	FRTB			FRNX		CLAI	TSUM1
						RUETB	TMNFTB
						TILLI	TMPFTB
							RDDTB

Herbage DM yields (*GRASS*) and potential yields (*YIELD*) were analysed. *GRASS* (kg DM ha^{-1}) is the biomass that has been cut and *YIELD* (kg DM ha^{-1}) is *GRASS* plus the remaining herbage yield on the field after the last mowing. The reduction factor for crop growth due to drought (*TRANRF*) is determined as the ratio between the actual and potential evapotranspiration and was analysed on an annual basis as the model's measure of drought. Daily values of *YIELD*, actual soil moisture (*SMACT*), leaf area index (*LAI*), the daily amount of photosynthetically active radiation (*PAR*) and the daily amount of *PAR* as intercepted by the grass crop canopy (*PARAB*), were compared with each other for 2003 (a dry year) and 2005 (a year in which *GRASS* was near the average *GRASS* for the period).

Time series analysis was additionally used to analyse simulated variables. This analysis makes it easier to explain oscillations and to detect outliers. The *decompose* function in the program environment R (R Development Core Team, 2009) was used, which separates the variable into a time series trend, with seasonal and random components based on symmetric moving averages.

Field data

To calibrate the LINGRA-N model for Slovenia, long-term datasets on grass sward herbage yield were needed. Datasets from three experimental sites were used: i) the S72 experiment in Ljubljana (central Slovenia: 46°2'59'' N, 14°28'16'' E, 297 m a.s.l.): permanent grass sward; ii) experiments in Jablje (central Slovenia: 46°8'59'' N, 14°33'31'' E, 307 m a.s.l.): cocksfoot (*Dactylis glomerata* L.) (J-DG), perennial ryegrass (*Lolium perenne* L.) (J-LP), and timothy grass (*Phleum pratense* L.) (J-PP); iii) experiments in Rakičan (north-eastern Slovenia: 46°39'15'' N, 16°11'22'' E, 186 m a.s.l.): cocksfoot (R-DG), perennial ryegrass (R-LP), and timothy grass (R-PP).

The experiments are described in greater detail in Pogačar *et al*. (2015).

Experiment S72 was carried out in Ljubljana in the period 1974-1993. Data on permanent grass sward DM yield are averaged from four iterations with fertilisation that provided the optimal herbage DM yield, which means annual fertilisation with 180 kg N

Table 4. Default parameter values in the LINGRA-N model that were calibrated for the period 1998–2013 (with missing years), and the results of the calibration for cocksfoot (J-DG), perennial ryegrass (J-LP) and timothy grass (J-PP) in Jablje, and for perennial ryegrass in Rakičan (R-LP).

Parameter and units	Default value	Calibrated for J-DG	Calibrated for J-LP	Calibrated for J-PP	Calibrated for R-LP
CLAI (ha ha^{-1})	0.8	0.8	0.3	0.2	0.3
DTSMTB (°C)	3	5	2	2	5
FRNX (-)	1	0.8	1	0.7	1
FRTB (kg kg^{-1})	0.165	0.2	0.2	0.135	0.165
KDIF (-)	0.6	0.6	0.5	0.5	0.5
LAICR (-)	4	4.5	4.75	4	5
LRNR (-)	0.5	0.55	0.35	0.5	0.35
MNDAT (Julian day)	-	132; 182; 242; 290	141; 173; 228; 280	135; 187; 245; 294	125; 164; 225
NMINS (kg N ha^{-1})	150	400	350	400	450
NMXLV (kg N kg^{-1} DM)	0.035	0.035	0.038	0.035	0.038
NRFTAB (kg kg^{-1})	0.7	0.7	0.7	0.8	0.9
RDDTB (°C)	10	9	9	10	11
RDI (cm)	40	30	30	30	40
RDMCR (cm)	40	40	50	40	80
RDRL (d^{-1})	0.05	0.065	0.035	0.035	0.035
RNFLV (kg N kg^{-1} DM)	0.01	0.01	0.013	0.01	0.007
RUETB (g DM MJ^{-1}PAR)	3	2.6	2.6	2.6	3.4
RUNFR (-)	0	0.08	0.04	0	0
SLA (ha kg^{-1})	0.0025	0.0025	0.0025	0.0025	0.0015
SOITMI (°C)	5	6	8	9	9
TDWI (kg DM ha^{-1})	300	200	300	200	300
TILLI (m^{-2})	7000	7000	6000	6000	6000
TMBAS1 (°C)	3	4	5	7	7
TMNFTB (°C)	–1	–3	–3	–3	–1
TMPFTB (°C)	3	5	1	1	1
TSUM1 (°C)	600	750	500	750	700
WREI (kg ha^{-1})	200	200	400	300	400

CLAI, remaining leaf area after cut; DTSMTB, increase in temperature sum as dependent on mean daily temperature; FRNX, optimal N concentration as fraction of maximum N concentration; FRTB, fraction of total biomass to roots at TRANRF=1; KDIF, extinction function for diffuse visible incoming light; LAICR, critical leaf area for self-shading; LRNR, maximum N concentration in roots as a fraction of maximum leaf N concentration; MNDAT, dates for grass cut; NMINS, total mineral soil N available at start of growth period; NMXLV, maximum N concentration in leaves as a function of development stage; NRFTAB, recovery fraction of fertiliser N applications; RDDTB, reduction function of RUE in dependence of daily solar radiation; RDI, initial rooting depth; RDMCR, crop-specific maximum rooting depth; RDRL, maximum relative death rate of leaves due to water stress; RNFLV - residual N concentration in leaves; RUETB - radiation use efficiency as function of development stage; RUNFR, fraction of precipitation lost by surface runoff; SLA, specific leaf area; SOITMI, initial value for soil temperature; TDWI, initial total biomass; TILLI, initial number of tillers; TMBAS1, base temperature for leaf elongation; TMNFTB, reduction factor of RUE as function of low minimum temperature; TMPFTB, reduction factor of RUE as function of soil temperature; TSUM1, temperature sum required for vegetative period (from emergence to flowering); WREI, initial weight of reserves (storage carbohydrates).

ha^{-1}, 120 kg P_2O_5 ha^{-1} and 165 kg K_2O ha^{-1}. The first fertilisation was set on 1st April and further ones on the day after each mowing. The three-cut system was used (Table 5). Soil data were obtained for upper soils up to a depth of 80 cm, which was set as the maximum rooting depth. Soil moisture in Ljubljana is 0.29 cm^{3}cm^{-3} at field capacity, 0.13 cm^{3}cm^{-3} at wilting point and 0.49 cm^{3}cm^{-3} at saturation (CPVO, 2014).

The experiments in Jablje and Rakičan were carried out between 1998 and 2013; data on herbage DM yield of grass monocultures are available. The minimum, average and maximum herbage DM yields for each year were obtained from various plots. In some years, no measurements were taken, and some years were omitted due to high deviations, mostly in connection with the age of the grass sward (Table 6). For example, in 2004, cocksfoot was

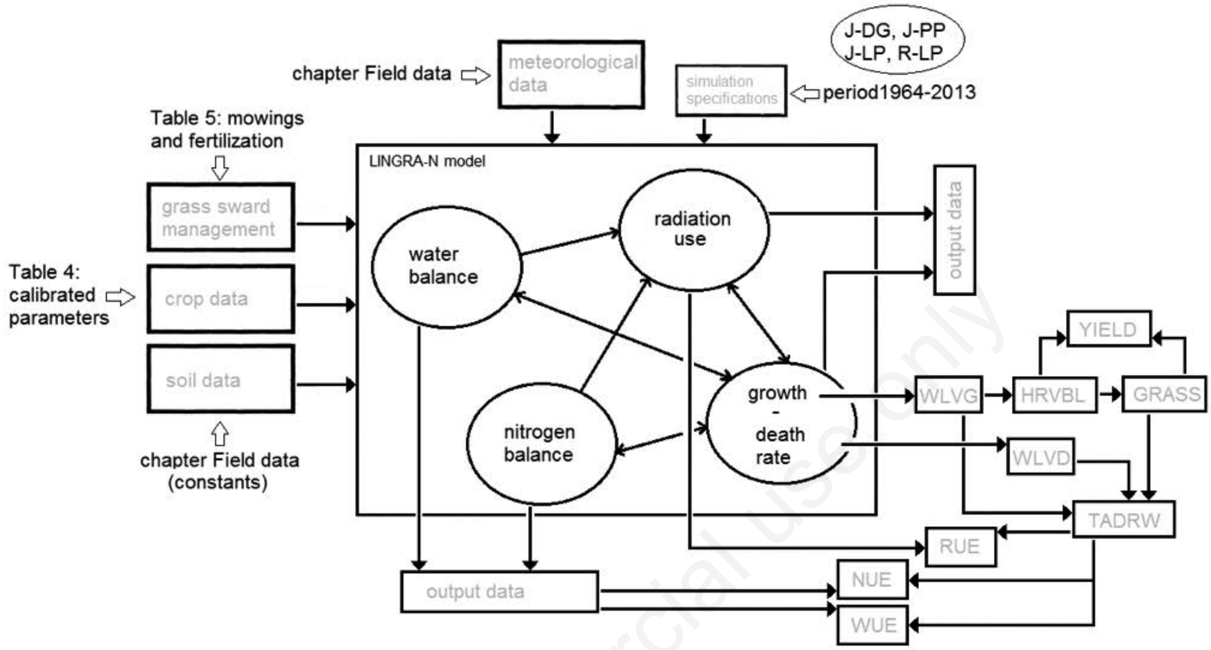

Figure 1. A simplified scheme of LINGRA-N model: input data, main parts of simulations and output data with some connections. WLVG, mass of green leaves in the field; HRVBL, harvestable leaf mass; GRASS, herbage DM yield; YIELD, potential yield (mass of harvestable leaves in the field plus herbage DM yield); WLVD, mass of dead leaves in the field; TADRW, mass of green and dead leaves in the field plus herbage DM yield; RUE, radiation use efficiency; NUE, nitrogen use efficiency; WUE, water use efficiency.

Table 5. Average mowing days used at the beginning of the calibration, calibrated values for simulations and nitrogen fertilisation rates for all study experiments.

Experiment	1st-2nd-3rd-4th mowing (Julian day) - average	1st-2nd-3rd-4th mowing (Julian day) - calibrated	1st-2nd-3rd N fertilisation rate (kg N ha^{-1})
S72	145-206-267	Not used for simulation	60-60-60
J-DG	136-187-242-287	132-182-242-290	60-50-46
J-LP	135-176-237-280	141-173-228-280	60-50-46
J-PP	141-191-245-294	135-187-245-294	60-50-46
R-LP	135-174-225	125-164-225	60-54-54
R-PP	134-178-243	Not used for simulation	60-54-54

S72, experiment in Ljubljana; J, Jablje; R, Rakičan; DG, cocksfoot; LP, perennial ryegrass; PP, timothy grass.

Table 6. An overview of the years in which herbage DM yield data from experiments in Jablje and Rakičan are available for the chosen grass species.

	Jablje			Rakičan		
	DG	LP	PP	DG	LP	PP
Calibration	1999, 2001, 2003, 2009, 2011, 2013	1999, 2003, 2007, 2009, 2011, 2013	1999, 2003, 2007, 2009, 2011, 2013	2001, 2007, 2009, 2013	1999, 2001, 2003, 2007, 2009	2001, 2003, 2007, 2009, 2013
Validation	1998, 2000, 2002, 2008, 2010, 2012	1998, 2002, 2006, 2010, 2012	2000, 2002, 2004, 2006, 2008, 2010, 2012	2000, 2010, 2012	2004, 2006, 2010, 2012	2000, 2006, 2010, 2012

DG, cocksfoot; LP, perennial ryegrass, PP, timothy grass.

in its fifth year so herbage DM yield was too small to be used for the analysis because the model simulates yield without considering the age of the grass sward. The R-DG experiment had to be eliminated due to a lack of years with reliable data. In the experiments, there were on average five (two to eight) varieties of cocksfoot, nine (five to fourteen) varieties of perennial ryegrass and six (four to nine) varieties of timothy grass. The average annual fertilisation rate was 156 kg N ha^{-1} in Jablje and 168 kg N ha^{-1} in Rakičan. Fertilisation with P_2O_5 and K_2O was annually adjusted to meet the optimum soil conditions. Days of fertilisation were set in the same way as in the S72 experiment. The four-cut system was mainly used in Jablje and the three-cut system in Rakičan (Table 5), where the amount of precipitation is much lower and growth conditions worse. Soil properties for the upper 80 cm are as follows: soil moisture is 0.36 cm^{3}cm^{-3} in Jablje and 0.22 cm^{3}cm^{-3} in Rakičan at field capacity, 0.14 cm^{3}cm^{-3} and 0.09 cm^{3}cm^{-3} at wilting point and 0.5 cm^{3}cm^{-3} and 0.43 cm^{3}cm^{-3} at saturation, respectively (Tajnšek, 2003).

Meteorological data

Daily data on global irradiation (kJ m^{-2}), minimum and maximum air temperatures (°C), early morning vapour pressure (kPa), average wind speed at a height of 2 m (m s^{-1}) and precipitation (mm) are needed as input for the LINGRA-N model. All meteorological data were acquired from the Meteorological Office at the Slovenian Environment Agency (ARSO, 2014). The nearest meteorological station for S72 is Ljubljana, at a distance of 3.5 km. For experiments in Jablje, the most representative station is Brnik Airport, at a distance of 13 km and for Rakičan, the Rakičan meteorological station is in close proximity (at a distance of 0.5 km). The distance between Jablje and Brnik, unfortunately, brings some uncertainty to the modelling results, especially in the case of summer local convective events but this is the only station nearby. Both Ljubljana and Brnik have the moderate continental climate of central Slovenia and Rakičan has the moderate continental climate of eastern Slovenia, which has the smallest amount of annual precipitation, most of which is summer showers and storms. Since no data were available for calculation of early vapour pressure in Brnik after 2000, values from Ljubljana were used. The impact of vapour pressure on final results was checked and is very small in comparison to other meteorological variables. Due to the unsuccessful calibration for S72 in Ljubljana, only meteorological data for the calibration period 1974–1993 were used, while for the other two stations 50-year (1964-2013) datasets were prepared. Some meteorological characteristics for the stations Brnik and Rakičan are presented in Appendix. The meteorological water balance (the difference between precipitation and potential evapotranspiration, calculated using the Penman-Monteith method) in the vegetation period was mostly positive in Brnik through the study period, with a water deficit in 1971, 1983, 1992, 1993, 1994, 2003 and 2011. Rakičan, on the other hand, had a negative water balance in 41 years out of 50 (Figure 2).

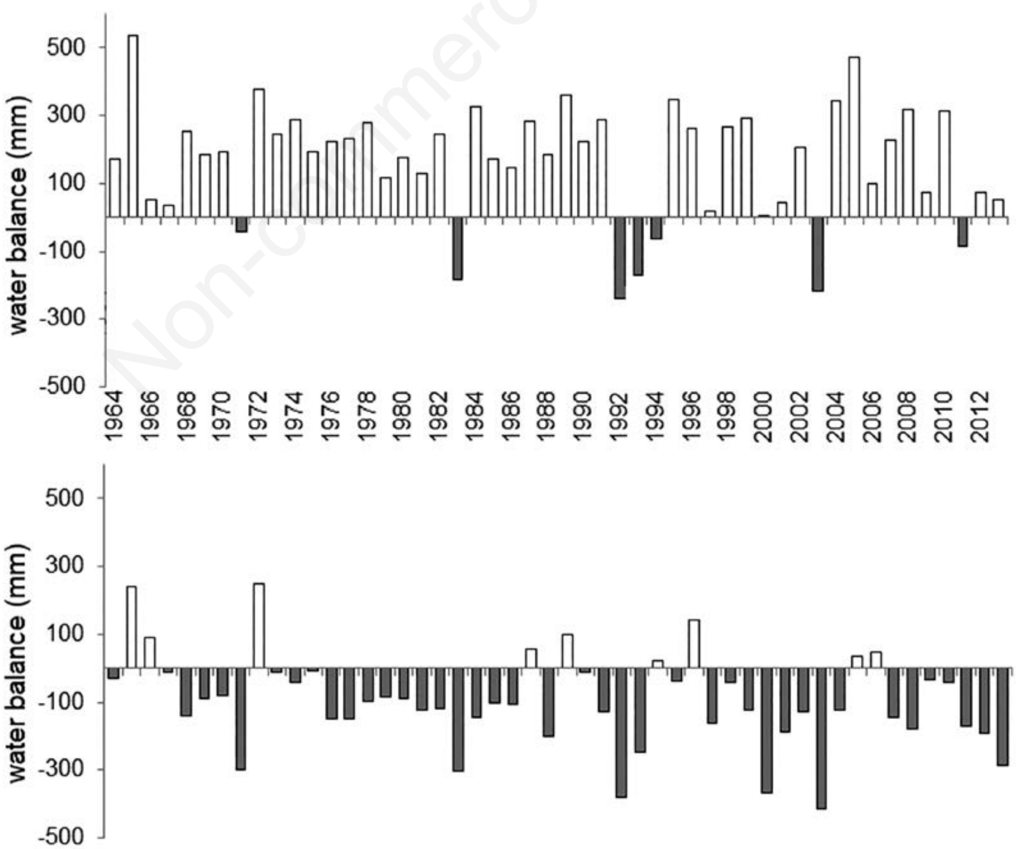

Figure 2. Meteorological water balance in the vegetation period by year in the period 1964-2013 in Brnik (upper) and Rakičan (lower).

Results

Calibration and validation of the LINGRA-N model

Differences between the pluri-annual averages of simulated and measured herbage DM yields were not big, ranging from 23 kg DM ha^{-1} (J-DG) to 364 kg DM ha^{-1} (J-PP). However, a common problem with modelling is too small standard deviations of simulated data, which causes too small inter-annual variation. Standard deviations of simulated yield for S72 (289 kg DM ha^{-1}) and R-PP (803 kg DM ha^{-1}) were the smallest, which was one of the criteria indicating that calibration in these two cases was unsuccessful. Further validation (Table 7) showed that, in terms of $RMSE_{\%}$, the results of LINGRA-N calibration were good for J-DG, S72 and J-PP, and fair for the other three. Considering even years only, the smallest $RMSE_{\%even}$ values were obtained for J-DG and J-PP, followed by S72 and J-LP. For S72 and R-PP, the systematic part of $RMSE_{\%}$ was very high, again indicating unsuccessful calibration. Willmott's index was also very low for S72, confirming that, despite good $RMSE_{\%}$ values, the model cannot be used to simulate herbage DM yield of permanent grasslands. Additionally, the R-PP case cannot be used in further simulation either, despite a very good Willmott's index, due to the already mentioned very unpromising $RMSE_{\%}$, its systematic part, and $RMSE_{\%even}$. To summarise, the calibration was not successful for the S72 experiment on permanent grassland and for timothy grass in Rakičan (R-PP). It was possible to simulate the production potential level but not the inter-annual variability, so the model was not appropriate for further simulations. For J-DG, the calibrated model fits the dynamics of measured annual yields very well. Although the model is useless without calibration, after calibration the simulated yield was firmly within the range of minimum and maximum measured values (Figure 3, left). The simulation was excellent for 2003, when in general the yield was very low due to extreme drought (Sušnik, 2014), and very good for 2001, 2011, 2012 and 2013 (Pogačar *et al*., 2015). In general, the fit for J-LP was a little worse than for J-DG, with best results for 2002, 2003, 2009 and 2011 (Figure 3, right). The calibration was not as good in Rakičan as in Jablje, although the measured herbage DM yield variation coefficient was quite high, at 44%. In Jablje, variation coefficients were 18% for DG, 33% for LP and 24% for PP.

Fifty-year simulations with the calibrated LINGRA-N model

Herbage DM yields (*GRASS*) and potential yields (*YIELD*) of three grass monocultures were simulated for the whole period 1964–2013 in Jablje, and for perennial ryegrass in Rakičan. *GRASS* (Figure 4) had the highest variability in the R-LP case, compared to the three cases in Jablje, where only few years were outstanding, with very low values. The decomposition of the time series of daily *YIELD* values (Figure 5) into trend, seasonal and random components did not show any changes in variability during the study period. However, in the second half of the period (after 1990) outliers appeared in *YIELD* in Jablje for all three grass monocultures. In the first half of the period there were none, and in the second there were six for J-DG *YIELD*, two for J-LP and five

Table 7. The root mean square error (RMS_E), its relative value ($RMSE_{\%}$) and its systematic ($RMSE_{\%s}$) and unsystematic ($RMSE_{\%u}$) parts, its relative value for even years ($RMSE_{\%even}$) and the index of agreement (d_w) for performance evaluation of the LINGRA-N model for the study experiments.

Experiment	$RMSE$ (kg DM ha^{-1})	$RMSE_{\%}$ (%)	$RMSE\%_s$ (%)	$RMSE_{\%u}$ (%)	$RMSE_{\%even}$ (%)	d_w
S72	1329	14	83	17	20	0.37
J-DG	1134	12	45	55	12	0.84
J-LP	1709	23	56	44	20	0.78
J-PP	1698	17	54	46	17	0.8
R-LP	2715	28	55	45	29	0.83
R-PP	1957	29	70	30	40	0.9

S72, experiment in Ljubljana; J, Jablje; R, Rakičan; DG, cocksfoot; LP, perennial ryegrass; PP, timothy grass. The table was partly published in Pogačar *et al*. (2015).

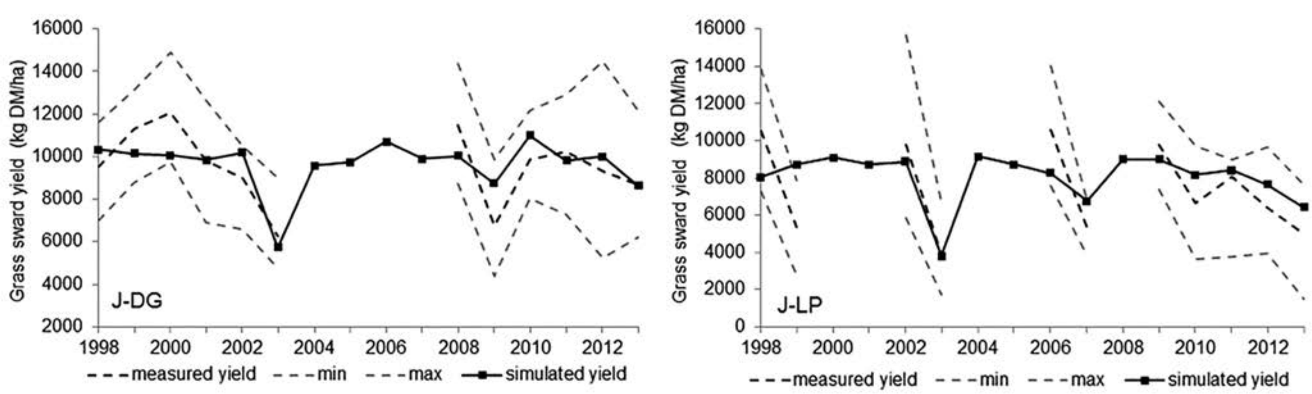

Figure 3. Annual herbage dry matter yield of cocksfoot (left) and perennial ryegrass (right) in Jablje: measured yield, minimum (min) and maximum (max) values of measured yield, and model simulated yield at the end of calibration.

for J-PP. With all three monocultures in Jablje, the lowest *GRASS* values (below 70% of the average value, which means yield reduction of 2.5 to 5.5 t DM ha^{-1}year^{-1}) were in 1992, 1993 and 2003. These were also the years with the lowest precipitation in summertime (47%, 59% and 53% of the average precipitation in 1964-2013, respectively) and in the vegetation period (55%, 62% and 59%, respectively). For all three monocultures, *GRASS* values were below 90% of the average in 2013, for DG in 2009, for LP in 1983 and 2007 and for PP in 1976, 1983 and 2012. The meteorological water balance was the lowest in 1992, 2003, 1983 and 1993. For R-LP, the lowest *GRASS* values were in 1983, 1993,

Table 8. Asterisks * denote the years with herbage dry matter yield (*GRASS*) below 90% of the average value (for R-LP below 70%) as well as lower reduction factor for crop growth due to drought (*TRANRF<0.9*).

Case	1983	1992	1993	2003	2007	2013
J-DG		*	*	*		*
J-LP		*	*	*		
J-PP		*	*	*		*
R-LP	*		*	*	*	*

J, Jablje; R, Rakičan; DG, cocksfoot; LP, perennial ryegrass, PP, timothy grass.

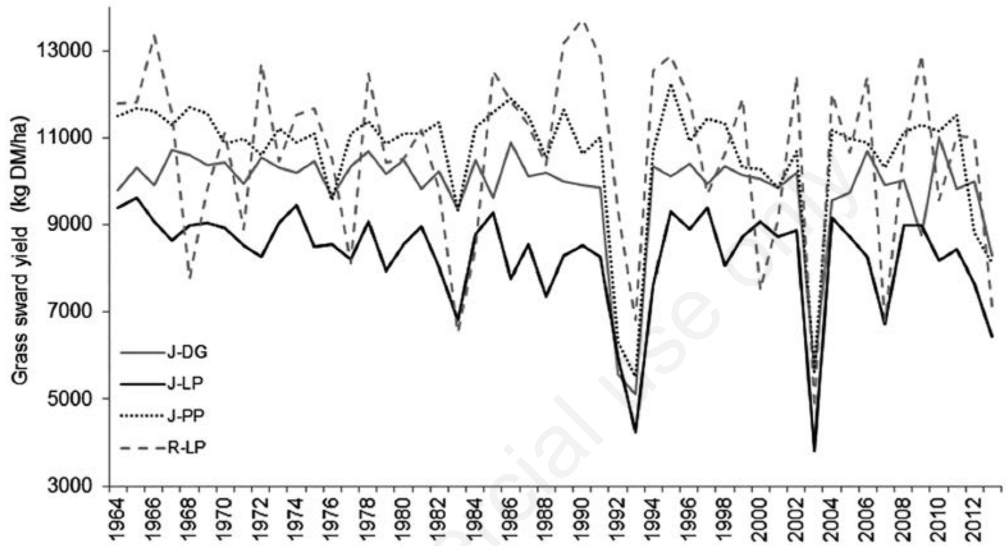

Figure 4. Annual herbage dry matter yield (GRASS) for all study cases for the entire period 1964–2013 (J, Jablje; R, Rakičan; DG, cocksfoot; LP, perennial ryegrass; PP, timothy grass).

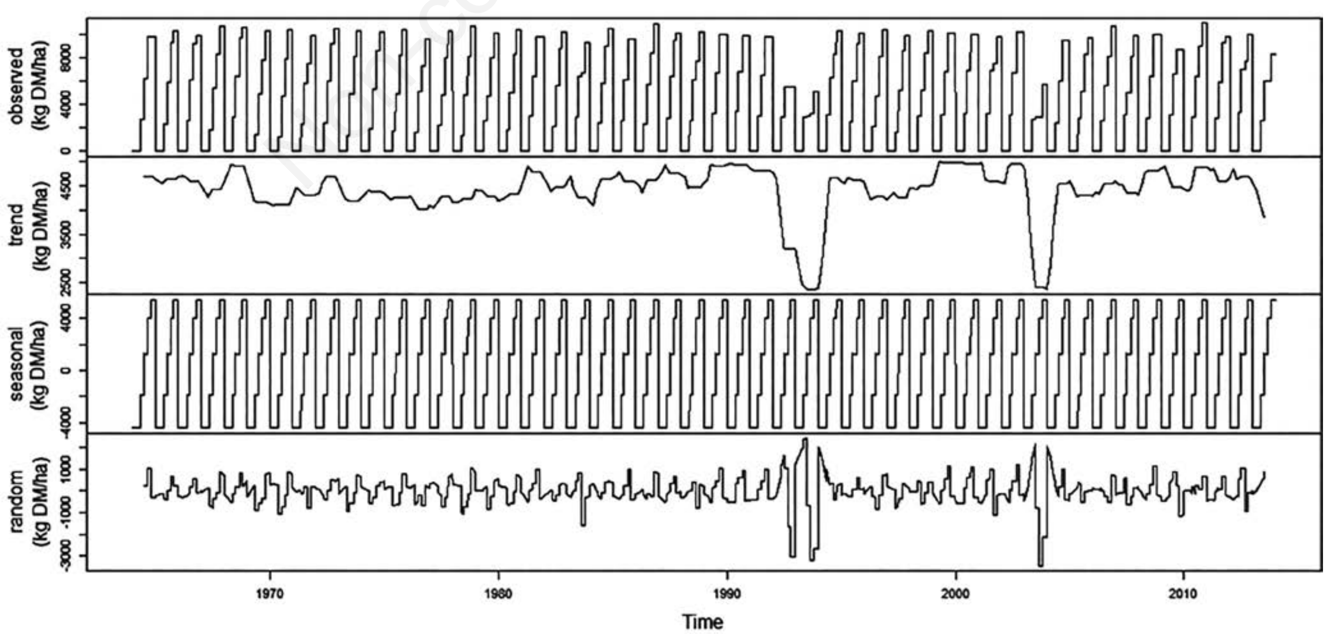

Figure 5. Decomposition of the time series of daily simulations of potential herbage dry matter yield (YIELD) of cocksfoot in Jablje (observed) in the entire period 1964-2013 into trend, seasonal and random components.

2003, 2007 and 2013. Major decreases in herbage DM yield thus mainly correlated with drought, as also confirmed in an analysis in which Sušnik and Pogačar (2010) identified 1992, 1993 and 2003 to be the driest years for grass sward in the period 1973-2009 at all six study locations in Slovenia. Furthermore, the years with the lowest *GRASS* values were also the years with the lowest *TRANRF* values (Table 8). The course of 50-year radiation use efficiency (*RUE*) was very similar to the *TRANRF* course, with the best match in very dry years. In Jablje, when *TRANRF* values were low, *RUE* stayed below 1.1 g DM MJ^{-1}PAR; however, when the water balance was favourable (*TRANRF*=1), *RUE* was between 1.3 and 1.7 g DM MJ^{-1}PAR, in Rakičan even over 1.9 g DM MJ^{-1}PAR.

Daily simulated values of some variables in 2003 and 2005

More information about grass monocultures' specific behaviour can be gained from simulated daily development of variables. A comparison of *SMACT* and *YIELD* values throughout 2003 and 2005 (Figure 6) showed that in the summer of 2003 there was undoubtedly a long period of drought. *SMACT* had already decreased towards wilting point by around 20 May (the 140th day) and stayed at a very low level into the end of August. Consequently, grass sward growth stopped or slowed down at the end of May. It was analysed whether various grass monocultures

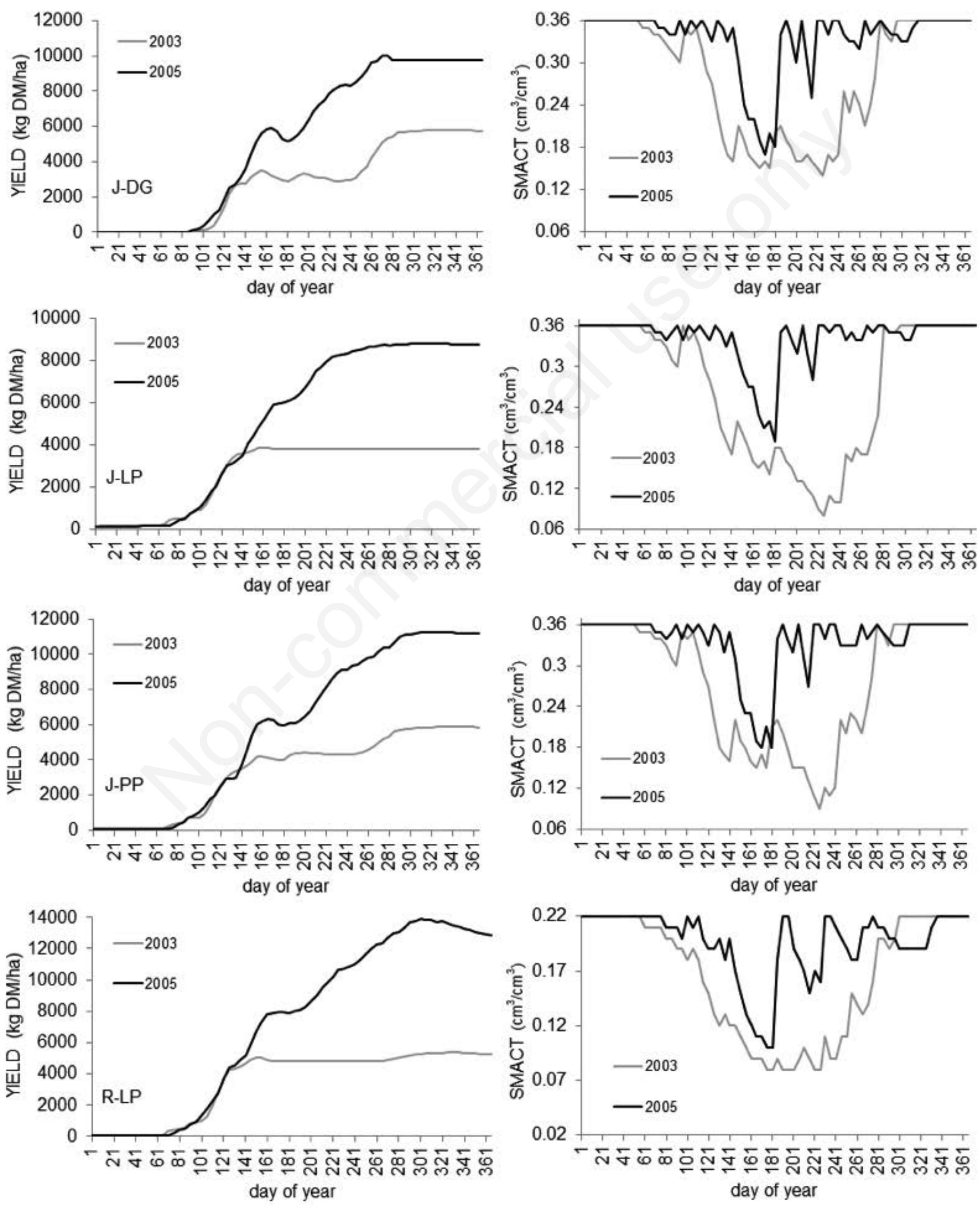

Figure 6. Potential yield (YIELD, left) and soil moisture content in the rooted zone (SMACT, right) of cocksfoot (J-DG), perennial ryegrass (J-LP) and timothy grass in Jablje (J-PP), and perennial ryegrass in Rakičan (R-LP) in the dry year of 2003 and the average year of 2005.

behaved in the model as they should, so in line with their usual behaviour during drought. Cocksfoot was best suited to drought conditions, *YIELD* having continued to increase slowly in the summertime. Perennial ryegrass died in 2003, when there was obviously no more *YIELD* increase even in autumn. On the other hand, timothy grass hibernated during the drought and resumed growth in the second half of September after *SMACT* increased. These characteristics can be also identified from the *LAI* graph (Figure 7). In the average year of 2005, *YIELD* increased fairly evenly throughout the season. Short breaks or slower growth were connected to lower *SMACT*.

Cumulative intercepted photosynthetically active radiation (*PARAB*) is directly connected to leaf area index (*LAI*) (Figure 7). In 2005, *LAI* decreased only at mowing. Although *LAI* did not increase much in Jablje after the third cut, its development was different in Rakičan, where only three cuts were made. Maximum *LAI* values there were around 6 m^2m^{-2} and in Jablje around 9 m^2m^{-2}. The *PAR* and *PARAB* graphs show that in 2003, a much higher share of *PAR* was intercepted in J-DG (59%) than in the others (32% in J-LP, 42% in J-PP and 27% in R-LP). This additionally explains the lower *YIELD* loss in J-DG in comparison to the others.

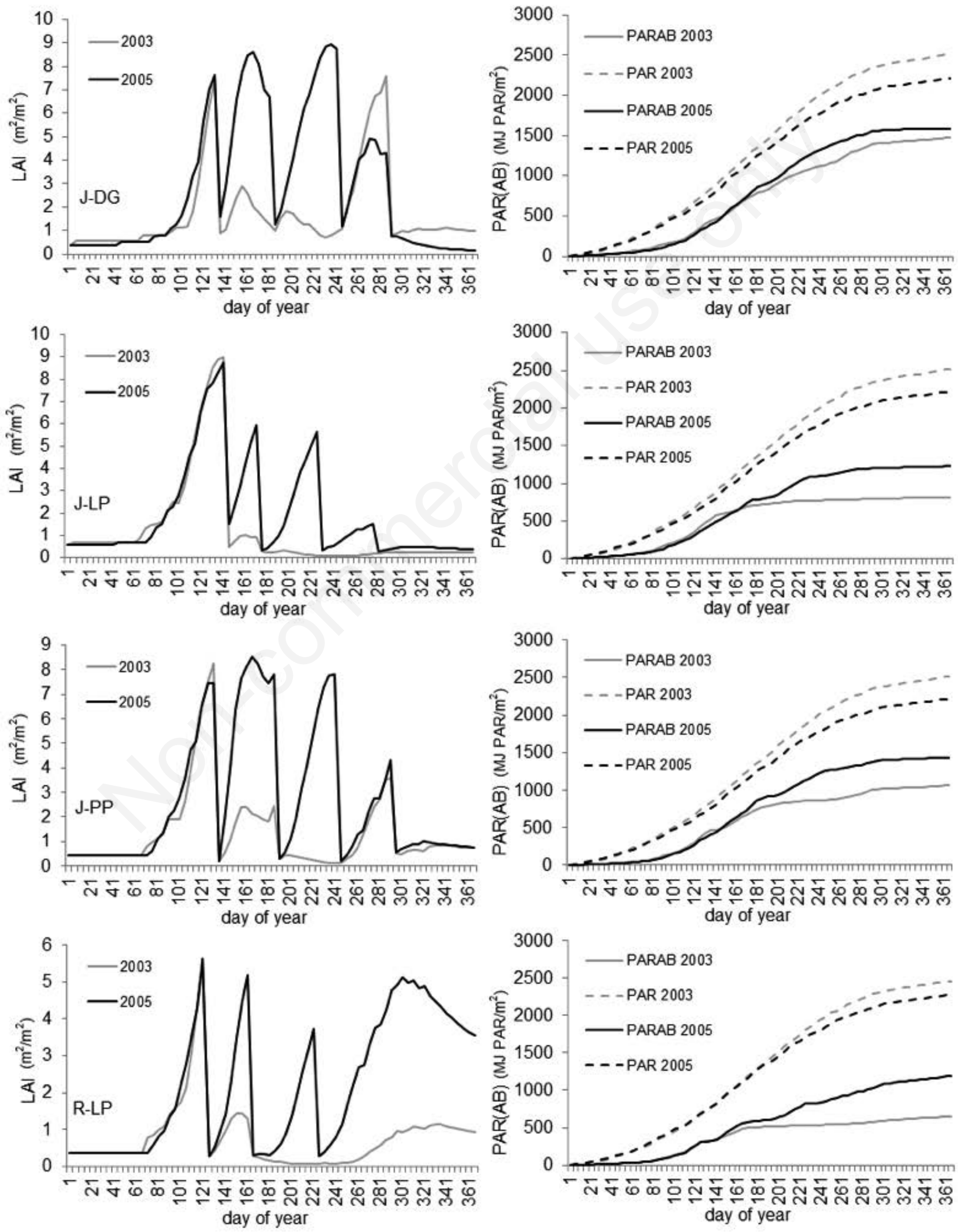

Figure 7. Leaf area index (LAI, left), the cumulative amount of photosynthetically active radiation (PAR), and the cumulative amount of PAR as intercepted by the crop canopy (PARAB) (right) of cocksfoot (J-DG), perennial ryegrass (J-LP) and timothy grass in Jablje (J-PP), and perennial ryegrass in Rakičan (R-LP) in the dry year of 2003 and the average year of 2005.

Discussion

Simulated grass growth and yield over a long period (such as 50 years), together with monitoring daily values during specific years, for various grass monocultures can have great value, revealing possible specific characteristics. For example, in 1992 *GRASS* in Rakičan was just 12% below the average, even though there was only 50% of the average precipitation in the vegetation period and only 46% in summertime. In 1993, the situation was the reverse - *GRASS* decreased by 36% against the average but the precipitation amount was higher by 72% of the average in the vegetation period and 67% in summertime. As has already been explained for one case study (J-DG) in Pogačar and Kajfež Bogataj (2015), the observed connections led to the testing of *YIELD* dependence on weather variables. *YIELD* was used instead of *GRASS* to avoid a direct influence of mowing dates on the final result. Among all input weather variables, calculated as the average or sum for the summer and for the vegetation period, none was linearly related to *YIELD*. It is assumed that the reason is in the strong outliers that were explained in the results and were connected with drought. However, Smit *et al*. (2008) claim that European grasslands' productivity correlates strongly with annual precipitation.

From daily values, it can be seen how, in the case of severe drought, only one or two cuts are needed. Management during a hot and dry summer season has to be adjusted to the specific conditions. In the model, average mowing dates are used, which is one of its big limitations as it can be far from reality in some years. On the other hand, the model has successfully simulated drought characteristics of cocksfoot, perennial ryegrass, and timothy grass as represented in the introduction, which implies that the model describes the behaviour of a specific monoculture very well and can be used as a support to a farmer's decision. It would be of great importance to implement also a calibrated model for perennial crops as farmers show interest in both - monocultures and perennial crops, but another research need to be done to gain better calibration results or to find another model with higher potential,

Bonesmo and Belanger (2002), among others, stated that drought stress has a major impact on *RUE*, as was also shown on *PAR* and *PARAB* graphs of daily values. The severity of the decrease in *RUE* due to drought depends on its intensity, duration and time of occurrence (Subbarao *et al*., 2005). The use of *RUE* as a tool to evaluate crop response to climate stress has not been fully evaluated. However, there is potential to use it to quantify the ability of a plant canopy to intercept *PAR* and to compare among cultivars or new crops (Hatfield and Prueger, 2015), which could be an additional measure to field cultivar testing experiments.

There was higher yield variability in Rakičan, which can be partly explained by soils with lower water holding capacities, where inter-annual weather fluctuation can have a greater impact. Other authors have also confirmed that grass sward herbage DM yields can vary strongly even under standard management conditions (Schapendonk *et al*., 1998; Trnka *et al*., 2005). From the point of view of achieving stability in forage production, there is a major need to analyse long time series on daily and yearly bases to determine possible trends and variability changes in the past, from which some projections can be done for the future. As can be seen, there has been a statistically significant increase in summer minimum and maximum daily temperatures over the period 1964-2013 (Appendix). A time series analysis of annual *YIELD* values showed a statistically significant (P=0.05) negative trend for J-LP (–24 kg DM ha^{-1}year^{-1}) and J-PP (–29 kg DM ha^{-1}year^{-1}). *TRANRF* time series are not stationary, so it can only be assumed from the form of the random component of the decomposed series that variability increased in the second half of the study period. Altogether, this may indicate more difficult future forage planning.

In relation to the model and the calibration, it is important to note another limitation - the model does not take into account the age of the ley; instead, each year growth is simulated anew. This can lead to greater discrepancies in years in which the ley in the field is older, which may have happened, for instance, with J-DG in 2009 and with J-LP in 1999. Calibration results could be better if field studies were conducted annually and on, for example, a two-year-old ley. Persson *et al*. (2014) highlighted the differences in calibration using grass sward of various ages. Their calibration results were much worse for first- ($RMSE_{\%}$=31%, d_w=0.36) than for second-year ley ($RMSE_{\%}$=22%, d_w=0.98). Furthermore, there is a parameter describing total mineral soil nitrogen available at the start of the growth period (*NMINS*) that had a strong role in reaching a high enough level of simulated herbage DM yield. Some measured values in Slovenia were around 80 to 100 kg ha^{-1} (there are not many measurements available) but it had to be set at 350 to 450 kg ha^{-1} (which was also measured in some cases) in the model or the production potential was too low, regardless of how other parameters were set. All limitations of the model in combination with the not-optimal availability of the data raised new questions about the appropriate choice of the model. However, in preliminary research some of the above (in the introduction) mentioned models were assessed and either there was a problem with additional data availability or options for the calibration.

For comparison, simulations of perennial ryegrass herbage yield in Rakičan (R-LP) were also made using parameters calibrated for perennial ryegrass in Jablje (J-LP). Results were much better than with default parameters but far from good. The form of the fitted curve is similar but there is quite a major difference in the level of production potential. Angulo *et al*. (2013) stressed the need for region-specific calibration of crop models used for Europe-wide assessments. However, some parameters remained unchanged for LP at the two locations: remaining leaf area index after mowing (*CLAI*), critical leaf area index for self-shading (*LAICR*), extinction coefficient for diffuse visible light (*KDIF*), optimal nitrogen concentration as a fraction of maximum nitrogen concentration (*FRNX*), maximum nitrogen concentration in roots as a fraction of maximum leaf nitrogen concentration (*LRNR*) and maximum nitrogen concentration in leaves as a function of development stage (*NMXLV*).

Conclusions

The LINGRA-N model was successfully calibrated for three grass monocultures but not for permanent grasslands. During the 50-year study period (1964-2013), the impact of drought on herbage DM yield was the most apparent. A connection between low herbage DM yield and high maximum air temperatures and small amounts of precipitation was indicated in outlying years. The model was very accurate in the simulation of drought characteristics of cocksfoot, perennial ryegrass, and timothy grass, which is important for countries like Slovenia where the drought is the main problem in the forage production.

Simulations enable us to test various environmental conditions and management practices but the uncertainty caused by input data, parameters calibrated in a certain period, model structure and concept has to be monitored. The quality of input data is thus of great importance, while well-planned long-term field experiments with additional measurements of growth components, soil moisture, *etc*. in the vicinity of meteorological stations can contribute to better simulations in the future. For future model assisted grassland research, experiments should be planned with the very same intention. The model should be calibrated for other various grass monocultures. Additionally, the LINGRA-N model should be improved. The first step would be to include annual mowing dates instead of average ones and afterwards to use new calibration methods possibly to obtain a calibrated model for permanent grassland. The relationship between the complexity of the model and data input was expected to be appropriate for conditions in Slovenia, but some limitations now seem to be difficult to overcome, so there should be also other models further assessed in this aspect.

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