COBISS Code 1.01

DOI: 10.14720/aas.2015.105.2.11

Agrovoc descriptors: agrometeorology, *Dactylis glomerata, grasses,* herbage crops, crop yield, drought, growth, simulation models, meteorological factors

Agris category code: p40, u30, f01

Simulation of herbage yield and growth components of Cock's foot (*Dactylis glomerata* L.) in Jablje using the calibrated LINGRA-N model

Tjaša POGAČAR[1], Lučka KAJFEŽ-BOGATAJ[2]

Received June 03, 2015; accepted August 20, 2015.
Delo je prispelo 03. junija 2015, sprejeto 20. avgusta 2015.

ABSTRACT

In the study the previously calibrated LINGRA-N model was used for a long term simulation (1964–2013) of the herbage dry matter yield (*GRASS*) and growth analysis of Cock's foot (*Dactylis glomerata* L.) in Jablje. Changes in the yearly *GRASS* variability are reflected in the appearance of outliers in the second half of the study period. The biggest reductions in *GRASS* are seen in the years 1992, 1993 and 2003. These are the driest years according to meteorological variables (high maximum and minimum air temperatures, low precipitation) and also according to the simulations, with the lowest reduction factor for crop growth due to drought. The potential yield (*YIELD*) is not linearly dependent on meteorological variables. Some growth components were compared on a daily basis in a dry year (1993) and an average year (1994). In 1993, for instance, 53 % of photosynthetically active radiation was intercepted, against 75 % in 1994. Seasonal development of the actual soil moisture content was linked to the development of the leaf area index and consequently to the mass of green leaves, to the roots mass, to the mass of dead leaves and to *GRASS*. The results highlight the need for further research, on field and with simulations. As regards the latter, we have to keep in mind that they inevitably involve various uncertainties.

Key words: simulation, LINGRA-N, cock's foot, herbage yield, drought, growth analysis

IZVLEČEK

SIMULACIJA PRIDELKA ZELINJA IN KOMPONET RASTI NAVADNE PASJE TRAVE (*Dactylis glomerata* L.) V JABLJAH Z UMERJENIM MODELOM LINGRA-N

Predhodno umerjen model LINGRA-N smo uporabili za simulacijo pridelka suhega zelinja (*GRASS*) in komponent rasti navadne pasje trave (*Dactylis glomerata* L.) v 50-letnem obdobju (1964–2013) v Jabljah. Izkazalo se je, da so se v drugi polovici obravnavanega obdobja pri simulacijah *GRASS* na letni ravni začeli pojavljati osamelci. *GRASS* je bil najmanjši v letih 1992, 1993 in 2003. To so tudi najbolj suha leta, tako na podlagi meteoroloških spremenljivk kot tudi na podlagi simuliranega faktorja zmanjšanja rasti zaradi suše. Potencialni pridelek (*YIELD*) ni linearno odvisen od meteoroloških spremenljivk. Določene komponente rasti smo na dnevni skali primerjali v sušnem letu 1993 in povprečnem 1994. V letu 1993 je bilo na primer prestreženega fotosintetsko aktivnega sevanja 53 %, v letu 1994 pa 75 %. Razvoj stanja vode v tleh tekom leta smo povezali z razvojem indeksa listne površine ter posledično z razvojem mase zelenih listov, mase korenin, mase odmrlih listov in *GRASS*. Rezultati opozarjajo na pomembnost nadaljnjih raziskav, tako poljskih poskusov kot tudi modelskih simulacij. Pri slednjih se moramo zavedati, da nosijo s seboj negotovosti iz različnih virov.

Ključne besede: modeliranje, LINGRA-N, navadna pasja trava, pridelek travne ruše, suša, analiza rasti

[1] univ. dipl. meteorol., University of Ljubljana, Biotechnical Faculty, Jamnikarjeva 101, SI-1000 Ljubljana, tjasa.pogacar@bf.uni-lj.si

[2] prof. dr., University of Ljubljana, Biotechnical Faculty, Jamnikarjeva 101, SI-1000 Ljubljana, lucka.kajfez.bogataj@bf.uni-lj.si

This article is based on research undertaken for a doctoral dissertation by Tjaša Pogačar. Supervisor: Prof. Dr. Lučka Kajfež-Bogataj.

Članek je nastal na osnovi raziskav v okviru doktorske disertacije Tjaše Pogačar. Mentorica: prof. dr. Lučka Kajfež-Bogataj.

1 INTRODUCTION

Annual grass production varies widely, even under standard management conditions (Laidlaw, 2009). The considerable year-to-year and seasonal variation in grassland production is of major importance, as production systems must allow for the risk of unfavourable weather conditions (Trnka et al., 2006). The dependence of grassland herbage dry matter (DM) production on weather factors and their interaction with soil conditions, sward composition and management have been shown in many analyses (Trnka et al., 2006; Barrett et al., 2005; Čop, 1992).

Even individual variables important in the description of grassland growth like leaf area index (*LAI*) are strongly weather dependent. For example, when there are sufficient mineral nutrients in the soil, the development of the canopy (with $LAI < 4$) of a perennial ryegrass crop during regrowth after winter or after a cut in spring time, essentially depends on the temperature (Lambert et al., 1999).

Drought is one of the most important weather phenomena, having a major impact on grass sward growth and herbage yield. In contrast to majority field crops, grasses which constitute major part of seminatural grasslands are perennial plants and grow for several years. According to Tehnološka priporočila ... (2008), the consequences of severe droughts affect grassland sward productivity over the next years through the changes in the botanical composition of the sward, which is adapting to new growth conditions. This effect is long term and it is not obvious in monocultures, which are sown every few years. Another problem is that when rain returns after a period of drought precipitation may not be in excess of evapotranspiration so soil moisture content may not increase significantly (Laidlaw, 2009). So grassland sward makes use of periods when enough water is available and the abundant spring growth is often followed by summer hibernation. Laidlaw (2009) states that early summer droughts may not have a long term impact on yield.

In Slovenia, periods of drought are becoming increasingly problematic for forage production in summer months, especially on lighter soils (Dolničar, 2013). For example, in 2006 74 % of agricultural area damaged by drought was under permanent grasslands and pastures (Sušnik, 2006). According to climate change scenarios for Slovenia by the middle of the century (Prihodnje ... , 2014) we can expect continuous problems with drought stress due to higher air temperatures and, at least in the southern part of the country, lower summer precipitation rates.

Appropriate knowledge and understanding of the impact of climate variability on agricultural production is therefore essential for devising an adaptation strategy (Ceglar and Kajfež-Bogataj, 2012). From this point of view, crop modelling is very important for studies of the impacts of weather and climate on production. In this paper the work with the calibrated LINGRA-N model (Wolf, 2012), is described. The aim was to use the model for a long term simulation (50-year period) of the herbage dry matter (DM) yield of a grass monoculture, which brings the opportunity to observe the year-to-year variability and yield declines in years of drought. Furthermore, the growth analysis was undertaken with the intention of better understanding the interactions between growth components. This has an important role in grassland management science, as growth analyses of grass crop are rare in Slovenia, on the field or in the lab. Even if there is one, the experiment cannot be maintained for such a long period of time. Additionally, some variables of water balance were studied – their influence on the yield, its year-to-year variability or their development during average and dry years. The comparison was made with year-to-year variability of meteorological data for the central Slovenia (meteorological station Brnik).

2 METHODS AND DATA

The simulations were made with the LINGRA-N model, which was previously calibrated with herbage DM yield data for cock's foot (*Dactylis glomerata* L.) in Jablje from the experiment (KIS, 2014) that was performed in the periods 1998–2003 and 2008–2013. The average measured herbage DM yield for both periods together was 9525 kg_{DM} ha^{-1} with the standard deviation of 1742 kg_{DM} ha^{-1} (Figure 1). The performance of LINGRA-N was good, with *RMSE%* = 12 % and with the index of agreement (Willmott, 1982) *d* = 0.84 (Pogačar et al., 2015).

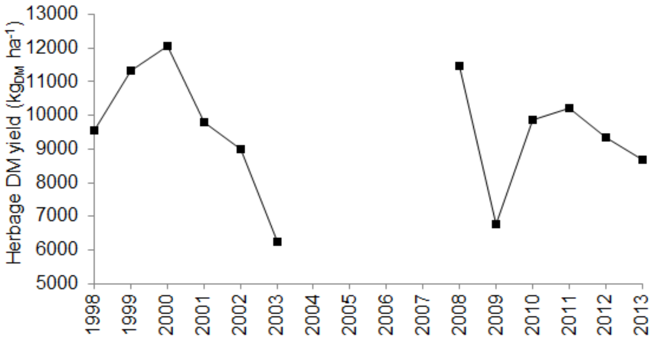

Figure 1: Average measured yearly herbage DM yield of cock's foot in Jablje for the periods 1998–2003 and 2008–2013 (data: KIS, 2014)
Slika 1: Povprečni izmerjen letni pridelek suhega zelinja navadne pasje trave v Jabljah za obdobji 1998–2003 in 2008–2013 (podatki: KIS, 2014)

2.1 Input data

The 50-year period of the simulation was set to 1964–2013 due to the availability of the meteorological data. For Jablje, the most representative meteorological station is Airport Ljubljana (Brnik). However, the distance of 12 km between the two brings some uncertainty to the modelling results, especially in the case of summer local convective events. The input for LINGRA-N includes daily data on minimum and maximum air temperatures (°C), precipitation (mm), mean wind speed (m s^{-1}), global radiation (kJ m^{-2}) and early morning vapour pressure (kPa), all obtained from the Slovenian Environment Agency (ARSO, 2014).

Air temperatures were lower at the beginning of the 50-year period (Figure 2, left) and so was global radiation (Figure 2, right). For the whole period, the average of average minimum daily air temperatures for the vegetation period (April-September) (*TminVP*) is 9.3°C, the average of average summer (June-August) minimum daily air temperatures (*TminS*) is 12.1°C, the average of average maximum daily air temperatures for the vegetation period (*TmaxVP*) is 22°C, and the average of average summer maximum daily air temperatures (*TmaxS*) is 25°C. In the second half of the period *TmaxS* dropped below this average in just seven years. *TmaxS* was extremely high in the years 2003, 2013, 2012, 1992 and 1983. It is clear that not only air temperatures but also their year-to-year variability are increasing. Something very similar holds true for the other presented air temperatures. However, the year-to-year variability of *TminVP* and *TminS* was higher in the first half of the period, due to a possibly non-climatic jump around the year 1978. Global radiation is increasing even more notably. Very high values were all reached after the year 2000: in 2011, 2003, 2009, 2000, 2007, 2012 and 2013.

The 50-year average of precipitation during the vegetation period (*RRvp*) is 734 mm, of which on average 396 mm fell in the summer time (*RRs*) (Figure 2, right). The decrease in precipitation is not obvious, but the variability increased in the second half of the 50-year period in both cases. There have lately been more years with low *RRvp* and especially with low *RRs*. *RRvp* was less than 500 mm in the years 1992, 2003, 1983 and 1993, while *RRs* was less than 250 mm in the years 1983, 1992, 2001, 2003, 2013 and 1993.

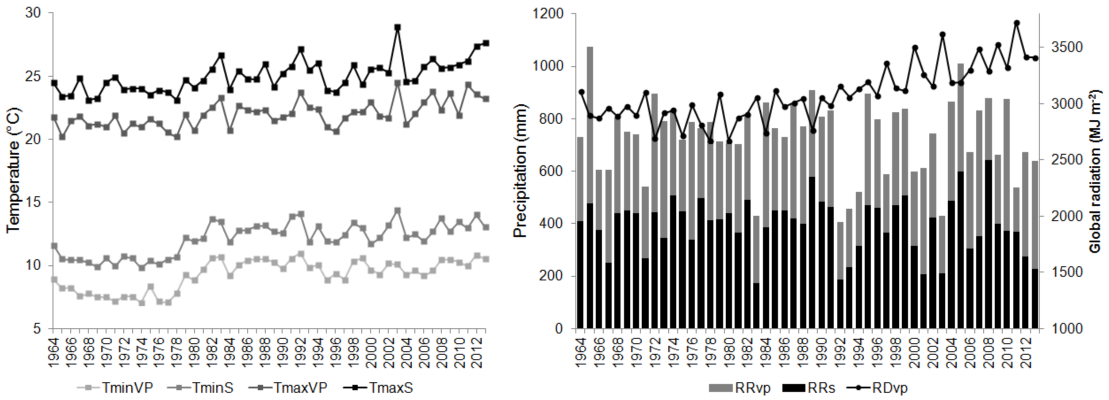

Figure 2: Left: Average minimum daily air temperature for the vegetation period (*TminVP*), average summer minimum daily air temperature (*TminS*), average maximum daily air temperature for the vegetation period (*TmaxVP*) and average summer maximum daily air temperature (*TmaxS*) in the period 1964–2013. Right: Precipitation during the vegetation period (*RRvp*), summer precipitation (*RRs*), and global radiation sum for the vegetation period (*RDvp*) in the period 1964–2013

Slika 2: Levo: Povprečna minimalna dnevna temperatura zraka za vegetacijsko obdobje (*TminVP*), povprečna poletna minimalna dnevna temperatura zraka (*TminS*), povprečna maksimalna dnevna temperatura zraka za vegetacijsko obdobje (*TmaxVP*) in povprečna poletna maksimalna dnevna temperatura zraka (*TmaxS*) v obdobju 1964–2013. Desno: Količina padavin v vegetacijskem obdobju (*RRvp*), poletna količina padavin (*RRs*) in vsota globalnega obsevanja v vegetacijskem obdobju (*RDvp*) v obdobju 1964–2013

The used soil type in Jablje is pseudogley-gley, deep and moderate, the texture is silty clay. The description can be found in Tajnšek (2003). Soil moisture content at saturation is 0.5 cm^3 cm^{-3}, soil moisture content at field capacity is 0.36 cm^3 cm^{-3} and soil moisture content at wilting point is 0.14 cm^3 cm^{-3}. The initial soil water content is set to field capacity (Pogačar et al., 2015). The rooted zone is changing with the growth of roots, every year from 30 to 40 cm. Four mowings are assumed and are set on fixed dates: 12 May, 1 July, 30 August and 17 October. The grass sward is fertilized on 1 April (60 kg_N ha^{-1}) and on the first day after the first (50 kg_N ha^{-1}) and the second (46 kg_N ha^{-1}) mowing.

Furthermore, calibrated crop and soil parameters are required as input. There are 27 of them, the most influential (Pogačar et al., 2015) are the thresholds for reductions of radiation use efficiency due to low minimum temperature (*TMNFTB = -3°C*) or high soil temperature (*TMPFTB = 25°C*), the leaf area index after mowing (*CLAI* = $0.8\ m^2\ m^{-2}$), the maximum light use efficiency (*RUETB* = $2.6\ g_{DM}\ MJ^{-1}{}_{PAR}$), the fraction of precipitation lost by surface runoff (*RUNFR = 0.08*), the initial number of tillers (*TILLI* = $7000\ m^{-2}$), the mineral soil nitrogen (N) available at the start of the growth period (*NMINS* = $400\ kg_N\ ha^{-1}$), the fraction of total biomass to roots under stressed conditions (*FRT = 0.2*) and the recovery fractions of fertiliser N applications (*NRFTAB = 0.7*).

2.2 Overview of output variables in the LINGRA-N model

From each simulation run two output files are obtained. One gives the daily results (as model time step is 1 day) for each simulated year (Table 1). The other contains yearly cumulative or average (depending on the characteristics of the variable) values for most of the variables (exceptions are marked grey in Table 1).

Table 1: Output variables of LINGRA-N simulated for each day (DM: dry matter, N: nitrogen). Variables for which model does not calculate yearly cumulative or average values are marked grey

Preglednica 1: Izhodne spremenljivke modela LINGRA-N, simulirane za vsak dan (DM: suha snov, N: dušik). S sivo so označene spremenljivke, za katere model ne izračuna letnih povprečij oz. vsot

Variable	Unit	Description
Water balance variables		
DRAIN	mm	cumulative drainage
ESOIL	mm	cumulative soil evaporation
IRR	mm	cumulative irrigation
RAIN	mm	cumulative precipitation
RUNOF	mm	cumulative runoff
SMACT	$cm^3\ cm^{-3}$	actual soil moisture content in rooted zone
WAVT	mm	available water in rooted zone
WTOT	mm	water in rooted zone
TRANS	mm	cumulative crop transpiration
Variables based on nitrogen		
NLIV	$kg_N\ ha^{-1}$	amount of N in living crop organs
NLOSS	$kg_N\ ha^{-1}$	N loss in dead crop organs and cut grass
NMIN	$kg_N\ ha^{-1}$	amount of organic N potentially available by mineralization from the soil
NMINT	$kg_N\ ha^{-1}$	mineral N directly available from soil and fertiliser
NNI	/	nitrogen nutrition index (range 0-1)
NUPT	$kg_N\ ha^{-1}$	N uptake by crop from soil
Crop variables		
DVS	-	development stage
LAI	$m^2\ m^{-2}$	leaf area index
PAR	$MJ\ m^{-2}d^{-1}$	daily amount of photosynthetically active radiation
PARAB	$MJ\ m^{-2}d^{-1}$	daily amount of PAR as intercepted by the crop canopy
TILLER	m^{-2}	number of tillers
TRANRF	/	reduction factor for crop growth due to drought/wetness (range 0-1)
WLVD	$kg_{DM}\ ha^{-1}$	mass of dead leaves in the field
WLVG	$kg_{DM}\ ha^{-1}$	mass of green leaves in the field
WRE	$kg_{DM}\ ha^{-1}$	mass of reserves (storage carbohydrates)
WRT	$kg_{DM}\ ha^{-1}$	roots mass
TSUML	°C	temperature sum from emergence
TADRW	$kg_{DM}\ ha^{-1}$	mass of green and dead leaves in the field plus herbage DM yield
GRASS	$kg_{DM}\ ha^{-1}$	herbage DM yield
YIELD	$kg_{DM}\ ha^{-1}$	mass of harvestable leaves in the field plus herbage DM yield

In the second output file there are also yearly values of nitrogen use efficiency (*NUE*, kg_{DM} kg^{-1}N), radiation use efficiency (*RUE*, g_{DM} $MJ^{-1}{}_{PAR}$) and water use efficiency (*WUE*, g_{DM} $kg^{-1}{}_{water}$).

In this paper some of the simulated variables are studied. In the first place the herbage DM yield of grassland (*GRASS*) and the potential yield (*YIELD*), in connection with input weather variables and the reduction factor for crop growth due to drought (*TRANRF*) on a yearly basis. The dependence of *RUE* on *TRANRF* is shown. To further describe the water status, the yearly development of the actual soil moisture content in the rooted zone (*SMACT*) is examined during a dry year (1993) and an average year (1994), in which *GRASS* is very close to the average *GRASS* for the whole period. Also, the daily amount of photosynthetically active radiation (*PAR*) and the daily amount of *PAR* as intercepted by the grass crop canopy (*PARAB*) are compared with each other in the two years. This kind of a comparison is also made for the variables of the daily growth of the grass crop like the mass of green leaves (*WLVG*), the roots mass (*WRT*) and the mass of dead leaves (*WLVD*). Furthermore, the leaf area index (*LAI*) progress during dry and average years is presented.

To better understand the simulation of those variables there is a short description based on Wolf (2012) of how they are calculated in the LINGRA-N model (sections 2.3 to 2.5).

2.3 Growth variables

Growth variable *PARAB* (MJ $m^{-2}d^{-1}$) is calculated as the daily amount of incoming *PAR* (MJ $m^{-2}d^{-1}$) times the fractional light interception:

$$PARAB = PAR(1 - e^{-K_{DIF} \cdot LAI}) \qquad (1)$$

where K_{DIF} is the extinction function for visible incoming radiation with the calibrated value of 0.6.

The daily assimilate production of the crop ($GTWSO_1$, kg_{DM} $ha^{-1}d^{-1}$) is dependent on *PARAB*, *RUE*, correction factors for temperature, high radiation levels, and atmospheric CO_2, and reduction factors for water and N stress (via *TRANRF* and nitrogen nutrition index *NNI*). The sum of $GTWSO_1$ and the available amount of reserves (*WRE*, kg_{DM} ha^{-1}) is labeled as $GTWSO_2$ (kg_{DM} $ha^{-1}d^{-1}$).

The sink limited increase in leaf area (*GLAISI*, ha $ha^{-1}d^{-1}$) is calculated from the number of tillers and the leaf elongation rate. The sink limited increase in total biomass (*GTWSI*, kg_{DM} $ha^{-1}d^{-1}$) is calculated as

$$GTWSI = \frac{GLAISI}{SLA \cdot (1 - FRT)} \qquad (2)$$

where *SLA* (with the calibrated value of 0.0025 ha $kg^{-1}{}_{DM}$) is a specific leaf area and *1-FRT* (with the calibrated value of 0.8) is the above ground allocation fraction.

The actual grass growth may switch between sink and source limited growth limitation. If $GTWSO_2 > GTWSI$, the growth rate (*GTW*, kg_{DM} $ha^{-1}d^{-1}$) is equal to *GTWSI* and the additional amount of assimilates results in an increase in reserves. If $GTWSO_2 \leq GTWSI$ then *GTW* is equal to $GTWSO_2$. The increase in leaf mass (*GLV*, kg_{DM} $ha^{-1}d^{-1}$) is calculated from the total growth rate *GTW* and the partitioning factor (*1-FRT*), to determine the mass of green leaves (*WLVG*, kg_{DM} ha^{-1}). With the *FRT* factor the roots mass is obtained (*WRT*, kg_{DM} ha^{-1}). The daily increase in *LAI* (*GLAI*, d^{-1}) is simulated as

$$GLAI = GLV \cdot SLA, \qquad (3)$$

with *SLA* as in (2).

Furthermore, the relative death rates of the leaves (*RDR*, d^{-1}) due to N shortage (with $NNI < 1$; RDR_n, d^{-1}) and due to ageing as dependent on the mean daily temperature (RDR_{tb}, d^{-1}), due to shading (with high *LAI* values; RDR_{sh}, d^{-1}) or due to drought (as dependent on *TRANRF*; RDR_{dr}, d^{-1}) are determined:

$$RDR = RDR_n + \max(RDR_{tb}, RDR_{sh}, RDR_{dr}). \qquad (4)$$

Next, the death rate of leaves (*DLV*, kg_{DM} $ha^{-1}d^{-1}$) is calculated from *RDR*, followed by the calculation of the mass of the dead leaves (*WLVD*, kg_{DM} ha^{-1}). The decrease in *LAI* (*DLAI*, d^{-1}) is calculated practically in the same way as the leaf death rate. Only to allow regrowth after, for example, a period of severe drought stress, *LAI* (m^2 m^{-2}) remains during the growth period always at least on the value of predefined *CLAI*. The change in the leaf area (*RLAI*, d^{-1}) is equal to *GLAI* minus *DLAI*

2.4 Herbage DM yield, potential yield and crop efficiency

For the calculation of the herbage DM yield (*GRASS*, $kg_{DM}\ ha^{-1}$), the harvestable leaf mass (*HRVBL*, $kg_{DM}\ ha^{-1}$) has to be determined first. It is equal to the green leaf mass in the field (*WLVG*) minus the leaf mass that remains in the field after mowing:

$$HRVBL = WLVG - \frac{CLAI}{SLA} \tag{5}$$

where *CLAI* is the leaf area index after mowing (0.8 $m^2\ m^{-2}$) and *SLA* is as in (2). *GRASS* increases at every mowing by the value of *HRVBL* on the mowing day. Potential yield (*YIELD*, $kg_{DM}\ ha^{-1}$) is determined by the equation

$$YIELD = GRASS + HRVBL. \tag{6}$$

For the crop efficiency simulations another variable *TADRW* ($kg_{DM}\ ha^{-1}$) is determined as

$$TADRW = GRASS + WLVG + WLVD. \tag{7}$$

It presents the mass of green and dead leaves in the field together with the herbage DM yield. Radiation use efficiency (*RUE*, $g_{DM}\ MJ^{-1}{}_{PAR}$) is derived at the end of the growth period from *TADRW* divided by the total intercepted solar radiation during the growth period. The calculation of water use efficiency (*WUE*, $g_{DM}\ kg^{-1}{}_{water}$) is similar: at the end of the growth period *TADRW* is divided by the total water amount used by evapotranspiration during the growth period.

2.5 Water balance

LINGRA-N calculates evapotranspiration and water balance in the same way as the WOFOST model (Supit and Van der Goot, 2003). The processes directly affecting the root zone soil moisture content are percolation, surface runoff, infiltration, crop transpiration and soil evaporation. The actual soil moisture content (*SMACT*, $cm^3\ cm^{-3}$) can be established according to Driessen (1986 op. cit. Supit and Van der Goot, 2003):

$$SMACT = \frac{IN_{up} + (IN_{low} - T_a)}{RD}\Delta t \tag{8}$$

where the rate of net influx through the upper root zone boundary (IN_{up}, $cm\ d^{-1}$) is

$$IN_{up} = P + I_e - E_s - SR \tag{9}$$

and the rate of net influx through the lower root zone boundary (IN_{low}, $cm\ d^{-1}$) is

$$IN_{low} = -PERC \tag{10}$$

and T_a ($cm\ d^{-1}$) is the calculated actual transpiration rate of crop, *RD* (cm) the calculated actual rooting depth, Δt the determined time step (1 d), *P* ($cm\ d^{-1}$) input daily precipitations, I_e ($cm\ d^{-1}$) from input recalculated effective daily irrigation (*not used – it is not a common practice to irrigate grass swards)*, E_s ($cm\ d^{-1}$) the calculated soil evaporation rate, *SR* ($cm\ d^{-1}$) the calculated rate of surface runoff and *PERC* ($cm\ d^{-1}$) the calculated percolation rate.

The method, introduced by Penman (1956, 1948 op. cit. Supit and Van der Goot, 2003) and adapted according to Choisnel et al. (1992 op. cit. Supit and Van der Goot, 2003), is used for daily totals of canopy transpiration and soil evaporation and is described in Supit and Van der Goot (2003). The reduction of the grass growth rate and the transpiration rate due to drought stress is calculated via:

$$TRANRF = T_a / T_p = \frac{SMACT - SMW}{SMCR - SMW} \tag{11}$$

where T_a and *SMACT* are defined as in (8), T_p ($cm\ d^{-1}$) is the potential transpiration rate of crop, *SMW* ($cm^3\ cm^{-3}$) soil moisture content at wilting point and *SMCR* ($cm^3\ cm^{-3}$) critical soil moisture content. *SMCR* is defined as the quantity of stored soil moisture below which water uptake is impaired and the plant closes its stomata. *TRANRF* affects *RUE* and the growth rate of the crop, the leaf death rate and the distribution of assimilates to the roots.

3 RESULTS AND DISCUSSION

As previously mentioned, there is great year-to-year variation of grassland herbage DM yields. Coefficient of variation for experimental herbage DM yield data in Jablje is 18 %. For instance, measured annual grassland herbage DM yields in Austria tend to vary within ±10-20 %, but during some years (e.g. 2003) these deviations can be much greater (Schaumberger et al., 2007). In the period 1995–2004, the average coefficient of variation for experimental grassland herbage DM yields in France was about 16 % (Smit et al., 2008).

The simulated *GRASS* (Figure 3) has about the same variability throughout the 50-year period, however, in the second half outliers start to appear, which can be alarming in terms of the negative effect of climate change.

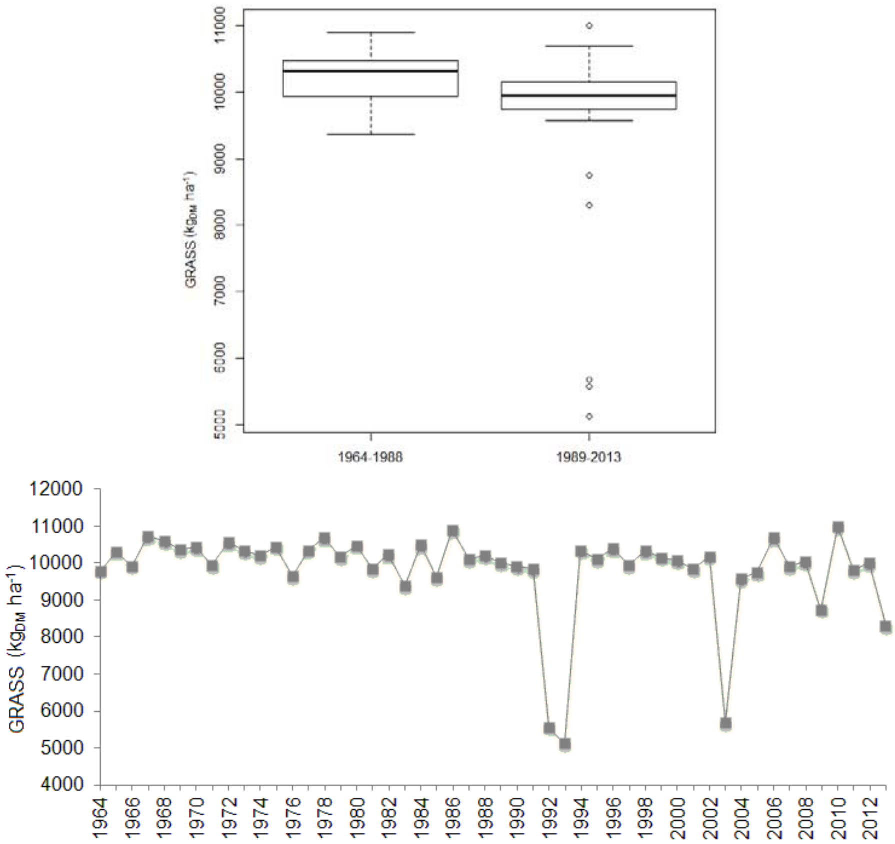

Figure 3: Upper: Boxplots of simulated yearly herbage DM yield (*GRASS*) of cock's foot in Jablje for the first (1964–1988) and the second (1989–2013) half of the 50-year period. Lower: Simulated yearly herbage DM yield (*GRASS*) of cock's foot in Jablje for the whole period 1964–2013

Slika 3: Zgoraj: Okvirja z ročaji za simuliran letni pridelek suhega zelinja (*GRASS*) navadne pasje trave v Jabljah v prvi (1964–1988) in drugi (1989–2013) polovici obravnavanega 50-letnega obdobja. Spodaj: Simuliran letni pridelek suhega zelinja (*GRASS*) navadne pasje trave v Jabljah za celotno obdobje 1964–2013

The biggest reductions in the simulated herbage DM yield are seen in the years 1992, 1993 and 2003 (approximately 4 t $ha^{-1}year^{-1}$). As it is seen in Figure 2, these are also years with very low precipitation in the summer and in the vegetation period. Only 47 % of average summer precipitation for the period 1964–2013 was measured in 1992, 53 % in 2003 and 59 % in 1993. For the vegetation period proportions were a little higher, 55, 59 and 62 %, respectively. Also, in the years 1992 and 2003 extremely high minimum and maximum daily air temperature averages were recorded for both the summer and the vegetation period. As regards global radiation, it was extremely high in the vegetation period of 2003. Altogether, it is clear that the *GRASS* reductions were due to drought conditions.

Sušnik and Pogačar (2010) studied indicators like the number of dry days and soil moisture deficit to define drought years for grass sward in six locations across Slovenia for the period 1973–2009, and compared them to drought reports published in Agrometeorological bulletins, which can be found in the archive of the Slovenian Environment Agency. In years 1992, 1993 and

2003 the most intense and the longest droughts were detected in all locations, which correspond to the simulation results.

Furthermore, the observed connections led to the testing of *YIELD* dependence on weather variables. *YIELD* was used in this case instead of *GRASS* to avoid a direct influence of the 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, there is none linearly related to *YIELD*. However, it can be again seen (Figure 4) that very low *YIELD* is connected to very high (maximum) air temperatures and very low precipitation. Smit *et al.* (2008) claim the grass sward production in Europe to be strongly correlated with the annual precipitation and less with the annual temperature sum or the length of the growth period. On the other hand, the 20-year experiment on permanent grassland in Ljubljana also showed only very small positive correlation between the annual precipitation and the herbage DM yield (Lekšan, 1995).

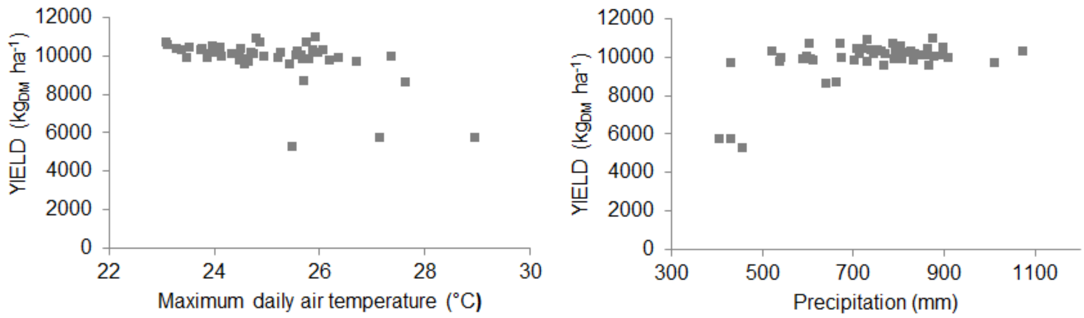

Figure 4: Scatterplots of the potential yield (*YIELD*) versus the summer average of maximum daily air temperature (left) and *YIELD* versus the vegetation period sum of precipitation (right) for cock's foot in Jablje for the whole period 1964–2013

Slika 4: Razsevna diagrama, ki prikazujeta potencialni pridelek (*YIELD*) v odvisnosti od poletnega povprečja maksimalne dnevne temperature zraka (levo) in v odvisnosti od količine padavin v vegetacijskem obdobju (desno) za navadno pasjo travo v Jabljah za celotno obdobje 1964–2013

The given years with the lowest *GRASS* were also the years with the lowest *TRANRF* (Figure 5). As *TRANRF* is the model's measure of drought conditions, these were detected as the driest years in the simulation. Also, in the years 1971, 1983, 1994, 2001, 2006, 2007, 2011, 2012 and 2013 *TRANRF* fell under 0.95, denoting dry years.

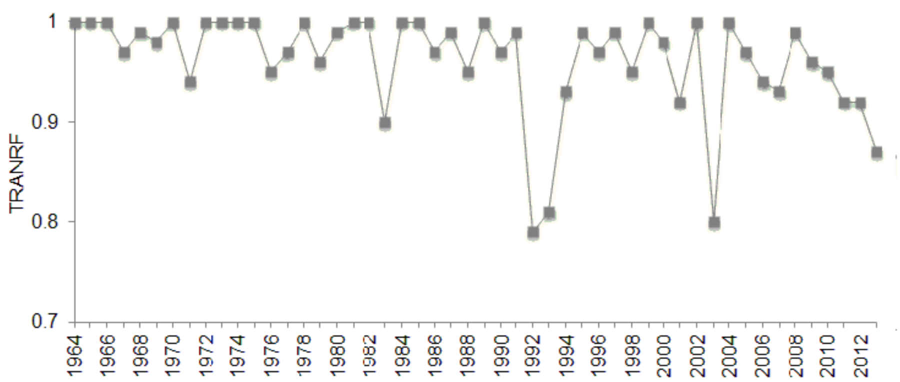

Figure 5: Simulated reduction factor for crop growth due to drought (*TRANRF*) for cock's foot in Jablje for the whole period 1964–2013

Slika 5: Simuliran faktor zmanjšanja rasti zaradi suše (*TRANRF*) navadne pasje trave v Jabljah za celotno obdobje 1964–2013

Smit *et al.* (2008) also claim that are herbage DM yields especially affected by droughts. Also similar as in our case, in Ireland, herbage DM yield reductions of 1.4 to 4.0 t $ha^{-1}year^{-1}$ have been estimated to be lost for intensively managed grassland in the driest regions due to limiting soil moisture availability (Brereton and Keane, 1982 op. cit. Laidlaw, 2009).

Drought stress has a major influence on *RUE* (Bonesmo and Belanger, 2002). This can be seen in Jablje as the course of *RUE* is very similar to the course of *TRANRF* (Figure 6). For *RUE* versus *TRANRF* (not presented) the coefficient of determination is $r^2 = 0.84$, which means that 84% of *RUE* variability can be explained with the changing *TRANRF*.

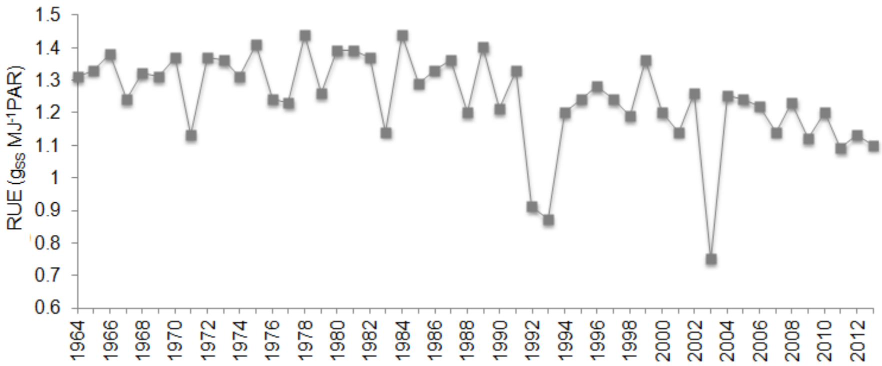

Figure 6: Simulated radiation use efficiency (*RUE*) of cock's foot in Jablje for the whole period 1964–2013
Slika 6: Simulirana učinkovitost izrabe sončnega obsevanja (*RUE*) navadne pasje trave v Jabljah za celotno obdobje 1964–2013

Water status can be also monitored as actual soil moisture content on a daily scale with variable *SMACT*. Figure 7 (upper right) shows a pattern of *SMACT* in the dry year of 1993 and in the average year of 1994. In 1993 *SMACT* stayed on a very low level from the beginning of May to the end of the August, while in 1994 it only fell to this level twice in the whole year. This is reflected very strongly in other variables. *YIELD* (Figure 7, upper left) was not increasing at all in the dry period of 1993, the same happened in 2003. In contrast, for example in the years 1994 and 2010 *YIELD* was increasing almost steadily throughout the vegetation period, only a little more slowly in the summer time. Naturally, *YIELD* depends on *LAI* (Figure 7, lower left), which remained under 2 $m^2 m^{-2}$ during the dry period of 1993. In 1994 *LAI* was below this value just at the beginning and at the end of the year, and on mowing days (four extreme falls of *LAI* can be seen). Otherwise it rose as high as 5 to 9 $m^2 m^{-2}$.

Cumulative *PARAB* in Jablje was 1100 $MJ_{PAR}\ m^{-2}year^{-1}$ in the dry year of 1993, which is 53 % of *PAR*, and 1650 $MJ_{PAR}\ m^{-2}year^{-1}$ in 1994, which is 75 % of *PAR* (Figure 7, lower right). For example, in the research of Wolf (2006), who made simulations of rye grass growth with LINGRA for five years for optimal water and nutrient supply, *YIELD* appears to increase from Wageningen (The Netherlands) to Bologna (Italy) to Sevilla (Spain). He claims this was caused by the length of the growing season and by cumulative *PARAB*, which increased for the three locations from 1200–1600 $MJ_{PAR}\ m^{-2}year^{-1}$ to 1700–2000 $MJ_{PAR}\ m^{-2}year^{-1}$ and 2700–2800 $MJ_{PAR}\ m^{-2}year^{-1}$, respectively.

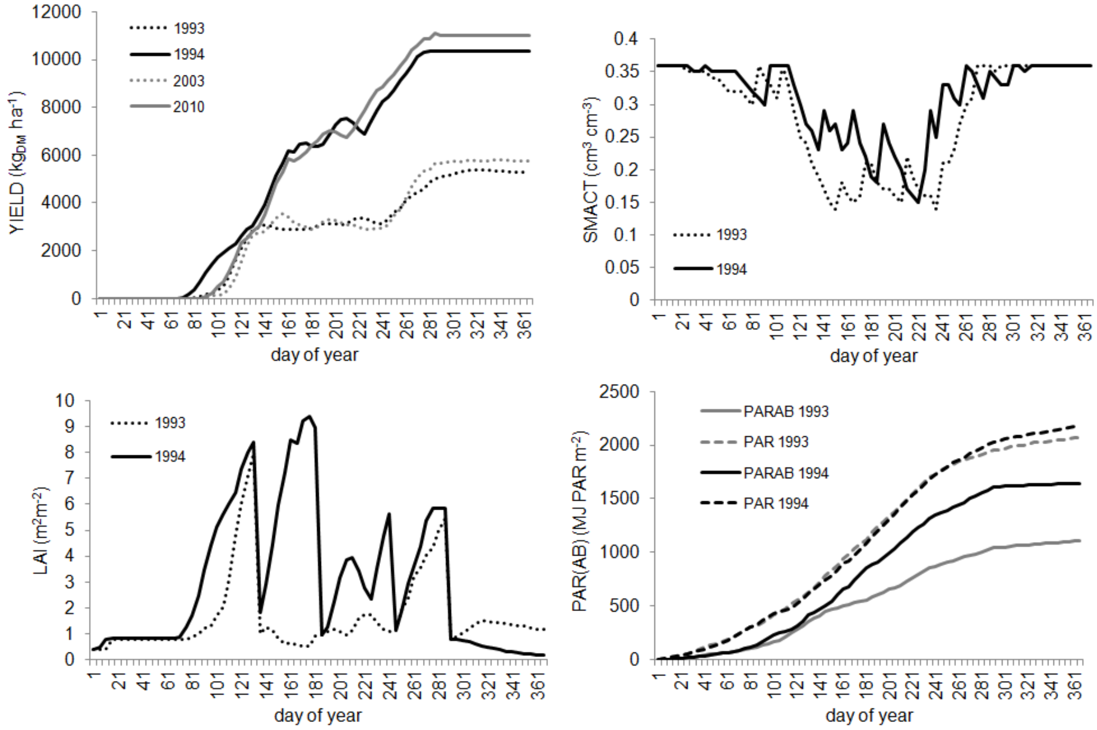

Figure 7: Simulated potential yield (*YIELD*, upper left), soil moisture content (*SMACT*, upper right), leaf area index (*LAI*, lower left), cumulative amount of photosynthetically active radiation (*PAR*) and cumulative amount of *PAR* as intercepted by the crop canopy (*PARAB*) (lower right) of cock's foot in Jablje in the dry year of 1993 and the average year of 1994 (*YIELD* also in 2003 and 2010)

Slika 7: Simuliran potencialni pridelek (*YIELD*, zgoraj levo), vsebnost vode v tleh (*SMACT*, zgoraj desno), indeks listne površine (*LAI*, spodaj levo) ter kumulativno fotosintetsko aktivno sevanje (*PAR*) in prestreženo fotosintetsko aktivno sevanje (*PARAB*) (spodaj desno) za navadno pasjo travo v Jabljah za suho leto 1993 in povprečno leto 1994 (*YIELD* tudi za leti 2003 in 2010)

According to Wolf (2006), the increase in *PARAB* results in a higher *YIELD* and in a much higher *WLVD*, because the higher biomass production results on average in a higher *LAI* and thus in more leaf senescence due to self-shading. The same can be said for the simulations in Jablje (Figure 7, Figure 8).

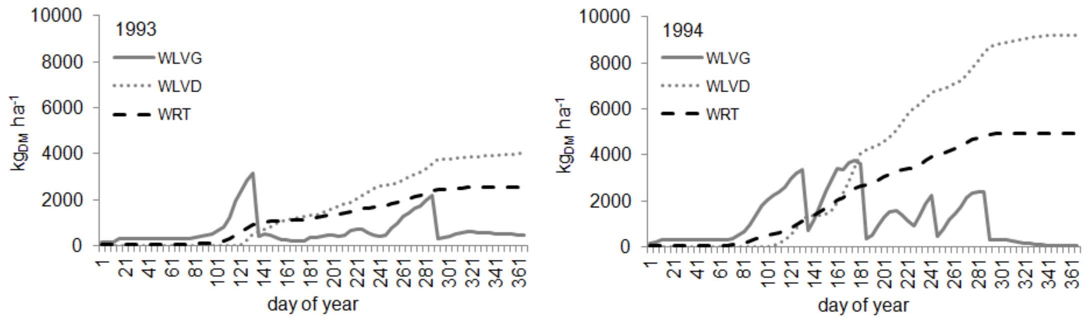

Figure 8: Simulated mass of green leaves (*WLVG*), mass of dead leaves (*WLVD*) and roots mass (*WRT*) of cock's foot in Jablje in the dry year 1993 (left) and in the average year of 1994 (right)

Slika 8: Simulirana masa zelenih listov (*WLVG*), masa odmrlih listov (*WLVD*) in masa korenin (*WRT*) navadne pasje trave v Jabljah v suhem letu 1993 (levo) in v povprečnem letu 1994 (desno)

As expected from the definition, the shape of the *WLVG* curve is the same as the shape of the *LAI* curve, due to constant *SLA*. In 1993, during the long summer drought *WLVG* was almost 0 all the time, so two intermediate mowings cannot be seen (Figure 8, left). On the other hand, four mowings are clearly seen in four extreme decreases of *WLVG* in 1994 (Figure 8, right). Because of the drought, roots also grew very slowly in 1993 and at the end of the growth period reached only half of the *WRT* that was reached at the end of 1994. What is more, the mass of dead leaves (*WLVD*) in 1993 was only 44 % of the *WLVD* in 1994, due to low available green biomass.

4 CONCLUSIONS

Fundamentally, this research shows the value of applying the calibrated LINGRA-N model for a 50-year (1964–2013) herbage yield simulation and growth analysis. It provides insights in the interactions between several weather and crop variables or their seasonal development and herbage yield variability. It is important to have an opportunity to better understand the growth components, and simulations can reveal their dynamics and impacts on herbage yield, based on weather and soil conditions. Overall, crop models are a very useful and important tool for this kind of research.

As regards the simulated herbage DM yield (*GRASS*), recent changes in its variability are reflected in the appearance of outliers in the second half of the study period. The biggest reductions in *GRASS* were detected in the years 1992, 1993 and 2003. These years were also recognised as years with very low precipitation and very high minimum and maximum daily air temperature averages in the summer and in the vegetation period, so we were able to conclude that the *GRASS* reductions were due to drought conditions. The given years with the lowest *GRASS* were also the years with the lowest reduction factor for crop growth due to drought (*TRANRF*). As the latter is the model's measure of drought conditions, these were detected as the driest years in the simulation, too.

Radiation use efficiency variability was strongly dependent on *TRANRF*. Drought had a major impact on the cumulative amount of *PAR* as intercepted by the crop canopy (*PARAB*), which reached just 53 % of *PAR* in the dry year of 1993. Seasonal development of the actual soil moisture content (*SMACT*) was linked to the development of the leaf area index and consequently to the mass of green leaves, to the roots mass, to the mass of dead leaves and to *GRASS*.

However, some of the obtained results remain indicative without confirmation of the simulated values through field measurements. Angulo *et al.* (2013) also recommend that future work should focus on obtaining more comprehensive, high quality data allowing application of improved methods for model calibration. For modelling it would be of great importance to plan grassland field experiments multiple years in advance that would, in addition to measurements of herbage yield, include measurements of variables or parameters like leaf area index, specific leaf area, leaf appearance rate, tiller density or mass of green leaves. Measurements of soil moisture content would also be useful. Further important factors include the vicinity of the meteorological station, the availability of soil data and, possibly, swards to be one to two years old. Naturally, this would be a major project with a great need of financial support.

The results highlight the need for further research, on field and with simulations. As regards the latter, we have to keep in mind that they inevitably involve various uncertainties. These uncertainties originate from input (meteorological, soil, management) data, from calibrated (for a specific period) model parameters, from model structure and concept. In order to identify potential problems caused by seasonal weather variability, which is increasing due to climate change, and to objectively assess its impact on the grassland production, it is necessary to perform various different simulations. For Slovenia, it would be of greater importance to make such simulations for permanent grasslands, but as for now the calibration has not been successful (Pogačar et al., 2015) we need to first obtain results for various grass monocultures and various locations, and try to proceed from there.

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