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Timely and regional monitoring of forage production in the European Union: the LINGRA model

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Abstract
This paper describes the current status of timely and regional monitoring of forage production in the European Union as implemented by the MARS project of the Space Applications Institute of the Joint Research Centre. A grass land module operational within the Crop Growth Monitoring System v4.2 (CGMS), called LINGRA is presented. LINGRA describes dry matter production and morphological development of well-fertilised pastures of perennial ryegrass, *Lolium Perenne*. LINGRA simulates dry matter production both for potential (irrigated) and for water-limited (rainfed) conditions. LINGRA was calibrated and evaluated (validated) on a set of common field experiments across Europe compiled by a FAO Subnetwork for lowland grassland. The evaluation of LINGRA on an independent sub set of this database indicated that the model predicted observed biomass values in time very well. The average error between observed and predicted biomass values, normalised to half of the observed biomass at the end of the growing season, averaged 13-15% on the level of potential production, and 17-21% on the level of water-limited production for the whole of Europe. Extension of the current model of perennial ryegrass with modules that describe optical and radar backscatter on basis of plant- and soil characteristics are proposed. To enable the model to evaluate environmental issues of grassland management in Europe, effects of sub-optimal nutrient availability have to be included.

Introduction

The MARS (Monitoring Agriculture with Remote Sensing) project of the Space Applications Institute of the Joint Research Centre aims at, among others, the use of deterministic crop growth models, Geographic Information Systems (GIS) and remote sensing to forecast yields of the most important crops of the EU member states (Meyer-Roux & Vossen, 1994). A major component of the project is the Crop Growth Monitoring System (CGMS; Vossen 1992, 1995), which utilizes the WOFOST crop growth simulation model (Van Diepen et al., 1989; Supit et al., 1994) for production estimation of arable crops at the level of potential and water-limited production. Potential production represents the absolute yield ceiling for a given crop in a given year on a given site, and is determined by solar radiation, temperature and crop characteristics. This ceiling can only be reached with a high input of fertilizers, irrigation (when needed) and pest, disease and weed control. Water-limited yield represents the yield ceiling without irrigation, where crop growth may be limited by rainfall during part of the growing season.

In 1994, the ‘client’ of the MARS project, i.e. the European Commission and in particular EUROSTAT and DG VI (Agriculture), requested JRC to extend CGMS to include the estimation of productivity of grasslands. Acreage of permanent pastures in the EU is large - 46 million hectares - in comparison with the total acreage of arable crops, i.e. 39 million hectares (EUROSTAT, 1994). Therefore, a tender was issued with the objective to develop and test algorithms to extend the MARS project’s regional agrometeorological models to include estimation of biophysical production from forage and pasture grasses across Europe. The DLO Institute for Agrobiology and Soil Fertility (AB-DLO) together with QRay-Agrimathica and the DLO Winand Staring Centre won the contract and started work in 1995. Conform to contract specifications, the model for grassland, called LINGRA, describes dry matter production and morphological development of a reference pasture (i.e. perennial ryegrass, *Lolium Perenne*) under standard management conditions throughout Europe. LINGRA was made operational within CGMS by August 1996. In CGMS, LINGRA is ‘dove-tailed’ with the WOFOST model for arable crops (Bouman et al., 1996a; Suverein, 1996), making use of common subroutines for e.g. evapotranspiration and water balance processes (Fig. 1). Output of LINGRA is comparable to that produced by WOFOST: simulated growth and development variables on the level of potential and water-limited production (i.e.above ground dry biomass, yield, leaf area index, development stage, and soil moisture status).

Model description

LINGRA (LINTUL-GRASS) was developed from the generic crop growth model LINTUL (Light INTerception and Utilization simuLator) as developed by Spitters (1987, 1990) and Spitters & Schapendonk (1989), and as such makes part of the series of crop growth simulation models of 'The School of De Wit' (Bouman et al., 1996b). An important concept behind LINTUL is that crop growth is proportional to the amount of light intercepted by the canopy (Monteith, 1977). The advantage of this concept is that the main process of crop growth is relatively simple to model and relatively easy to parameterise from experimental data (relative to more detailed crop growth models such as for instance WOFOST). Below, the most important growth processes of LINGRA are summarily explained (a more detailed description is given in Bouman et al. (1996a).

Model initialisation
LINGRA simulates dry matter production from January 1 to December 31, without a region-specific crop calendar. Crop growth starts when a pre-defined (soil) temperature condition is fulfilled. The 10-day moving average of daily temperature acts as an estimate of soil temperature. When this variable exceeds a certain threshold value, crop growth starts. Using this approach it was possible to estimate the onset of crop growth properly over a range of years and areas varying from Iceland to Portugal (see below).

Crop growth rate
The daily growth rate is formulated according to the concept that growth is proportional to the amount of light interception by the canopy:

$$\Delta W_t = f_t \,.\, PAR_t \,.\, E_t \; (\mathrm{g\ m^{-2}\ d^{-1}})$$

where ΔW_t is the growth rate at day t (g dry matter m^{-2} d^{-1}), f_t the fraction of PAR intercepted by the foliage, PAR_t the incoming amount of Photosynthetically Active Radiation (MJ m^{-2} d^{-1}), and E_t the light utilisation efficiency (g dry matter MJ^{-1} PAR).

Light interception
The fraction of interception of photosynthetically active radiation by the grass canopy, f_t (-), is calculated from the leaf area index, LAI (m^2 leaf surface m^{-2} ground surface), and the extinction coefficient for PAR, *k* (-):

$$f_t = (1-e^{(-k.LAI)}) \; (-)$$

It is assumed that the fraction of light that reaches the ground through the crop exponentially declines with leaf area index. The amount of intercepted radiation, PARint (MJ m^{-2}), therefore becomes:

$$PARint = f_t \,.\, PAR_t = PAR\,(1- e^{(-k.LAI)}) \; (\mathrm{MJ\ m^{-2}})$$

The intercepted energy is used to assimilate CO_2 from the atmosphere by photosynthesis. The efficiency of light utilisation in photosynthesis is variable in time and depends on the nutrient status (not modlled) and on environmental conditions.

Light utilisation efficiency

The light utilisation efficiency, E_t, has a maximum value of 3 g MJ^{-1} (called E_{max}). Three factors affect the actual value of E_t: light intensity itself, temperature and water availability (in case of water-limitation). When temperatures become favourable for crop growth after winter, growth may first be restrained by temperature (sink-limited growth conditions), while later on, growth is driven by source availability (under the assumption that nutrients and water are sufficiently available). The reduction on the light use efficiency is effective during a small temperature traject, i.e. from 3 to 8° C for pastures located in the North of Europe. Below 3° C, the light use efficiency is set to zero, while above 8° C, E_t is not restrained by temperature. The reduction in light use efficiency due to moisture stress is made effective by multiplying E_t with the ratio of the actual transpiration rate, T_a, over the potential transpiration rate, T_p.

$$E_t = T_a/T_p\ f(T)\ f(PAR)\ E_{max} \quad (g\ MJ^{-1})$$

Within CGMS, two fictive 'grass varieties' were introduced to meet regional conditions in Europe as best as possible (see below: model calibration and validation). For the so-called 'Northern variety', the light use efficiency, E_{max}, has a value of 3.0 g dm MJ PAR^{-1} , whereas for the 'Southern variety', a value of 2.5 g dm MJ PAR^{-1} was used. This reflects the finding that photosynthesis follows a saturation curve, e.g. the increase of the rate of photosynthesis declines per additional unit of radiation. As a result, the light use efficiency declines in Southern Europe under higher radiation intensities.

Sink and source interaction

Actual crop growth is defined as the minimum of assimilate demand by the crop (sink) and assimilate availability as determined by environmental conditions (source). The demand for assimilates is determined by the rate of leaf area expansion divided by the specific leaf weight of newly formed leaves taking into account the amount of assimilates needed to support root growth. The rate of leaf area expansion is calculated as the product of tiller number, average width of leaves and a temperature dependent rate of leaf elongation.

At initialisation, crop growth is started from a pool of reserve carbohydrates. This amount of carbohydrates is available for initial growth of leaves, and may also support regrowth of leaves after cutting in cases when the supply of newly assimilated carbohydrates is insufficient.Thus, the reserve pool act as a reservoir in which carbohydrates are stored when the amount of available assimilates exceeds the actual demand, and which may be used when the actual demand exceeds the available amount of newly produced assimilates

Leaf area development

Net growth of leaves is the result of leaf growth and leaf senescence. Leaf growth is determined by the amount of assimilates available at the actual daily crop growth rate. Leaf senescence is calculated by means of a relative death rate, which is computed from the leaf area index and the ratio of the actual transpiration over the potential transpiration. A high leaf area index leads to internal shading of the lower leaves which results in leaf senescence.

Leaf area development is also affected by grassland management, e.g. mowing, grazing or rotational grazing. In LINGRA, two standard management options are implemented (to be selectde bybthe user): periodic mowing and mowing at a constant biomass level.

Tiller dynamics

There is a close relation between formation of tillers and productivity of grasses (Schapendonk & de Vos, 1988). Each tiller produces new leaves, and in principle each axil of a leaf contains a bud to produce new tillers. The maximum number of tillers emerging from new buds is 0.69. Just after mowing this number is much less, i.e. 0.335. The increase in number of tillers, $DTIL_n$ (tiller m^{-2} d^{-1}), is calculated as the product of appearance rate of new leaves, $DLEAF_n$, (leaf $leaf^{-1}$ d^{-1}), the sum of the relative rate of tillering, RTR (tiller $tiller^{-1}$), and relative tiller death rate, TDR (tiller $tiller^{-1}$), times the amount of tillers (tiller m^{-2}):

$$DTIL_n = DLEAF_n\ TIL_n\ (RTR - TDR) \quad (tillers\ m^{-2}\ d^{-1})$$

Potential evapotranspiration and soil water balance
Potential evaporation and crop transpiration is calculated using the same Penman formulations as already implemented in CGMS as subroutines of the WOFOST model. Also for the calculation of volumetric soil moisture content in the root zone - needed to calculate evapotranspiration - use is made of water balance routines already existent in CGMS, i.e. WATPP and WATFD for the levels of potential production and water-limited production respectively. This way, a high degree of compatability and comparability between manner of crowth monitoring of arable crops by WOFOST and of grassland by LINGRA is assured (both highly desired features in the MARS project). Hijmans et al. (1994) and Supit et al. (1994) give details on the subroutines for evapotranspiration and water balances in CGMS.

Model calibration and validation

For calibaration and validation of LINGRA, an extensive dataset with experimental data on forage production was made available by the Institute of Grassland and Environmental Research (IGER) in Aberystwyth, United Kingdom. This database was produced in the project "Predicting production from grassland' of the FAO Subnetwork for lowland grassland (Corrall, 1984, 1988). It contains standardised experimental data of grassland experiments during three to five years on 35 sites thoughout Europe with different climatic and soil conditions, using two cultivars of *Lolium Perenne* (perennial rye grass) and *Phleum pratense* (Timothy). Because of the large quantity and good quality of data on *Lolium Perenne*, this grass was chosen to serve as standard/reference crop for calibration of LINGRA for CGMS. Data of 15 experiments that approached unrestrained growth - characterised by dry matter yields above 16 t/ha - were selected for calibration on the level of potential production. Four model parameters were used in the calibration process: the maximum light use efficiency, E_{max} ; the parameter CLAI that quantifies the remaining LAI after cutting, and two parameters that determine the reduction of the light use efficiency at sub-optimal temperatures. Calibration was done with a specially designed program for the calibration of large crop growth models (Stol et al., 1992), using a controlled random search algorithm adapted from Price (1976) for finding the global minimum of a function with constraints on the independent variables. The calibration results showed that two fictive grass 'varieties' (characterised by two distinctive sets of the four calibration parameter values and by common values for all other model parameters) could be introduced to satisfactorily describe the experimental data set in the whole of Europe: one for the North and one for the South of Europe. The division line between the two fictive varieties is given in Figure 2.

LINGRA was evaluated (validated) on an independent subset of the FAO database. A graphical and quantitative analysis of model performance showed that the model predicts observed biomass values in time very well. The average error between observed and predicted dry biomass values, normalised to half of the observed biomass at the end of the growing season, averaged 13-15% on the level of potential production, and 17-21% on the level of water-limited production for the whole of Europe. Figure 3 shows the results of LINGRA on two contrasting locations with respect to overall model performance: Wageningen (the Netherlands) and Carmagnola (Italy). These two locations show the lowest and highest normalized average error in dry biomass prediction over two years (1983 and 1984) in both the potential and the water-limited simulations, respectively 700 (Wageningen) and 1900 (Carmagnola) kg/ha. Based on these evaluation results, it was concluded that LINGRA was sufficiently accurate for the purposes of the MARS project in the simulation of potential and water-limited growth and development of a reference grassland under standard management conditions in the whole of the EU, covering a broad range in climatic conditions and soil types.

Further opportunities
Having a validated forage model available within CGMS - ready to monitor potential and water-limited forage production on a European scale - new opportunities and alternative applications of this module arise.

Link with remote sensing data
LINGRA could be linked with optical and remote sensing subroutines to improve its monitoring capabilities of actually occurring growth conditions (Bouman, 1996; Bouman, 1995). Recently, the link between crops and remote sensing signals was extended by linking models of soil water balance to subroutines that describe radar backscatter of the whole soil-crop complex (Figure 4). It was shown that radar backscatter as measured by ERS could be largely explained by variation in (simulated) soil water status (Bouman, 1996; Bouman et al., 1997). This possible interface could stimualte the application of radar-backscatter data in Europe, and could have spin-off to other (dry land) areas as well.

Early drought detection
LINGRA could be used in its water-limited setting as a kind of early warning system for drought stress. Perennial ryegrass has the majority (85%) of its root system in the shallow soil layer of 0-40 cm below soil surface. Therefore, it could be a good 'indicator crop' for drought stress before other crops with deeper rooting systems react to drought conditions.The possible link with remote sensing data could enhance these capabities of LINGRA greatly (see above).

Environmental research
Environmental problems on grassland, mainly related to the low recovery of nutrients from organic manure and partial to sub-optimal recovery of inorganic nitrogen fertiliser are an important issue in grassland research and a continuous topic for debate in the EU. When LINGRA is extended with the possibility to simulate forage production under sub-optimal nutrient availability, an new tool comes available which may help to develop nitrogen management on grassland, adapted to regional agro-climatic conditions. The LINGRA model could serve as a tool for diagnosis of environmentally sound nitrogen management on grassland in the EU.

Climate Change
The assessment of the impact of climate change on forage production in the EU is a topic that can be effectively researched with LINGRA. New relations between atmospheric CO_2 concentration and photosynthesis (as function of radiation and temperature, obtained from experimental research) should then be introduced.

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Figure 1. System description of the LINGRA model in CGMS

Figure 2. Division line between the use of the fictive ‘Southern’ and ‘Northern’ varieties (calibration parameter value sets; see text) in the European Union.

Figure 3a-d. Observed and predicted total above ground biomass of *Lolium Perenne* on the level of potential and water-limited production for Wageningen (NL) in 1983 and 1984.
WILLEM: ZET IN DE FIGUREN DE NUMMERS A-D, EN ZET IN ONDERSCHRIFT WELKE POTENTIAL EN WELKE ATER-LIMITED IS. KAN JE OOK AANGEVEN OF DIT EEN VALIDATIE SET IS (OF EEN CALIBRATIE SET)?

Figure 3e-h. Observed and predicted total above ground biomass of *Lolium Perenne* on the level of potential and water-limited production for Carmagnola (**I**) in 1983 and 1984.
WILLEM IDEM ALS BOVEN

Figure 4. The integrated environment for crop growth modelling and remote sensing. Within rectangles the modules that describe the relations between radar backscatter and crop biomass (a) and the module that describe the relation between optical remote sensing and leaf area index (b).