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Description of the growth model LINGRA as implemented in CGMS

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2 Description of LINGRA

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2.1 Grass modelling

The growth of crops obeys certain physiological principles. These may be described in qualitative terms but, to a certain extent, the various growth processes can also be quantified in response to the environment by mathematical equations. By linking the equations to each other, a mathematical model is obtained that, for convenience, can be written as a computer program. Such a quantitative model enables the prediction of crop growth rates and yields under a variety of environmental and management conditions. Models are useful as a tool for the farmer to assist in his decisions on management operations (e.g. in scheduling of irrigation, fertiliser application and crop protection). A crop model may also be used for land use evaluation or for yield forecasting as for instance in CGMS (see Chapter 1). For both purposes, two modelling approaches can be distinguished: a simple static model without description of process rates, and a dynamic model where state variables change in accordance to fluctuating process rates. Static models have the advantage of a small number of parameters and a simple algorithm. The dynamic approach, however, has the advantage of greater flexibility. In addition, it gives more insight into the sensitivity of underlying processes that interact with fluctuating climatic factors. This facilitates the extrapolation of effects on the individual organ level, established under constant conditions, to the level of a whole crop growing in an environment with fluctuating conditions. Various intermediate approaches are, of course, applicable, such as for instance in most generic models intended for regional applications. In such models, both static and dynamic descriptions are used. The LINGRA model is of such an intermediate type. It is derived from a model approach, later called LINTUL (Light INTerception and Utilisation simulator), proposed by Spitters (1987, 1989, 1990). The integration level is kept high and the number of processes has been restricted to key parameters only. Only a small number of processes involving these key parameters is simulated dynamically. On the other hand, parameters that have relatively little impact on crop growth, or of which knowledge is scarce, have been treated using the static approach. The additional advantage of using the LINTUL approach is that the number of model parameters is relativey low (compared to, for instance, WOFOST), which makes the model more easy to parameterize (Spitters, 1990).

For a thorough overview on the development of dynamic crop growth simulation models, the reader is referred to e.g. Penning de Vries & van Laar (1982), van Keulen & Wolf (1986), and Penning de Vries et al. (1989). Reviews on the various approaches followed in crop growth simulation and examples of their application have been given by, among others, Loomis et al. (1979), Penning de Vries (1983), Whisler et al. (1986), and Wisiol & Hesketh (1987), Spitters et al., (1989), and Bouman et al., (1996).

2.2 Special features of grass growth compared to arable crops

In contrast to arable crops, most grasslands are frequently defoliated due to herbivory or management activities. The consequence of defoliation is reduction of photosynthesis rate. After defoliation, new leaves must be formed in order to assure continuation of production. These new leaves can only grow because significant amounts of carbohydrates were stored in the stubble of the plants before defoliation. These so-called 'storage carbohydrates' serve as a buffer that is emptied during a short period after cutting when photosynthesis is too small to provide for the necessary substances for regrowth. The reserves are replenished when light interception and photosynthesis rate are increasing again. Subsequent periods of defoliation and regrowth lead to an alternating sequence of temporary shortage of assimilates, just after defoliation, and a period of assimilate surplus at full light interception. These occurrences are characteristic for almost all grasses and must be accounted for in grass growth models. Assimilate demand and assimilate supply depend differently on environmental conditions. Assimilate demand (the sink) is strongly associated with leaf elongation, leaf appearance and tillering rate, whereas assimilate supply is controlled by photosynthesis and thus by the amount of light that is intercepted by the canopy. In LINGRA, the dynamic fluctuations of the assimilate demand (ΔW_d) and the assimilate supply (ΔW_s) are simulated semi-independently. The term 'semi-independent' is used because each day, crop growth rate is estimated from the most limiting process, either ΔW_d or ΔW_s as the driving rate variable. All other state variables are derived from the growth rate at that particular day and are not integrated independently for source and sink limitation.

2.3 Model description

LINGRA was developed on two hypothetical levels of production as defined by De Wit & Penning de Vries in 1982:

- Potential production. Growth occurs in conditions with ample supply of water and nutrients and growth rates are determined solely by weather conditions (solar radiation and temperature).
- Water-limited production. Growth is limited by shortage of water during at least part of the growing period but nutrients are in ample supply. Growth rates are determined by weather conditions (solar radiation, temperature, rainfall, potential transpiration) and by soil characteristics.

In both situations, the crop is optimally protected against pests, diseases and weeds. In the next paragraphs, the model statements on crop growth and development as implemented in LINGRA at these two levels of grass production are described.

The appendices give a variable name listing (I), a listing of example input files (II), and a listing of the model source code in Fortran (III).

2.3.1 Initialization and cutting regime

LINGRA runs with a defined set of initial parameter settings that are read from an external file. For instance initial leaf area, LAI_c (-), is set at a value of 0.1 and the storage pool present in the stubble after the winter period is 200 kg ha^{-1}. In principle, these parameter values can be changed by the user according to local field conditions; default values have been implemented in CGMS as derived from parameterization (Chapter 3).

Crop growth after the winter period is initialized when the 10-day moving average of daily temperature (actual conditions; particular year of simulation) is higher than a given base temperature Tb_1. When the temperature is lower than Tb_1 growth and development are set to zero.

In CGMS, a fixed cutting regime (read from external input file) is imposed that is the same for the whole of Europe: the crop is mown at the beginning of each month starting after spring (re-)growth and ending at winter dormancy. In principle, options have been implemented to change the cutting interval, or to make the time of cutting dependent on the accumulation of a certain amount of (above-ground) biomass. Leaf area index (LAI) is reset each time that the crop isdefoliated.The storage pool is dynamically simulated over the cuts according to the dynamic interactions between storage and remobilisation.

2.3.2 Crop growth rate

LINGRA (LINTUL GRASS) is based on the concept used in LINTUL (Light INTerception and Utilisation simulator; Spitters, 1987, 1988) that growth is proportional to the amount of light intercepted by the canopy:

$$\Delta W_t = f_t \,.\, PAR_t \,.\, E_t \; (g\ m^{-2}\ d^{-1}) \qquad (2.1)$$

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). PAR is the visible part of solar radiation ('light'; wave bands 400-700 nm), and is about 50% of the total solar radiation (wave bands 300-3000 nm). The proportionality between crop growth rate and intercepted light has been recognized by many authors (Gaastra, 1958; Biscoe & Gallagher, 1977; Monteith, 1977), and the seemingly constancy of this proportionality factor has contributed much to its present popularity (review by Gosse et al., 1986). The calculation of total dry matter at the end of a growing season is simply obtained by integration of Equation 2.1 over time. The yield of the harvested product, Y (g dry matter m^{-2}) can be calculated by multiplying total biomass (W) by the harvest index, HI (-), being the share of the harvested product in total dry matter:

$$Y = \int (f_t PAR_t \,.\, E_t)\, HI \quad (g\ m^{-2}) \qquad (2.2)$$

In LINGRA, the harvest index is replaced by dynamic grass specific partitioning factors, intercepted radiation is calculated from leaf area index, and light use efficiency is made dependent on temperature, level of PAR and possibly occurring water stress. This has the advantage of replacing integrated quantities by variables defining instantaneous processes, i.e. replacing 'state variables' by 'rate variables'. In that way, it becomes easier to introduce the effects of stress conditions (Spitters & Schapendonk, 1989).

2.3.3 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, *k* (-):

$$f_t = (1-e^{(-k.LAI)}) \; (MJ\ m^{-2}) \qquad (2.3)$$

The amount of intercepted radiation, PARint (MJ m^{-2}), therefore becomes:

$PARint = f_t . PAR_t = PAR (1- e^{(-k.LAI)})$ (MJ m^{-2}) (2.4)

The calculation of LAI is explained in Paragraph 2.3.6. The intercepted energy is used to assimilate CO_2 from the atmosphere by photosynthesis processes. The efficiency of light energy utilisation in photosynthesis processes is variable in time and dependent on the nutrient status and environmental conditions.

2.3.4 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).

Light intensity
The light utilisation efficiency is relatively high at low light intensities and declines at higher light intensities because photosynthesis follows a saturation curve. The effect of the daily integrated light intensity on the light dependent efficiency decline, called f(PAR) (-), is depicted in Figure 2.1. The light utilisation efficiency is constant at its maximum value below 5 MJ PAR and declines linearly above this threshold.

Temperature
Photosynthesis is activated above a certain temperature threshold, Tb_1 (°C). Thereafter, light utilisation increases linearly with temperature up to a maximum value at Tb_2 (°C), after which it remains constant with further increases in temperature (Figure 2.2). The factor that accounts for the effect of temperature on E_t is called f(T) (-). In Figure 2.2, the maxixmum temperature range is from -20 to 40 °C; temperature values outside this range have the same f(T) values as at these maximum values (i.e. no effects of extreme temperature values are taken into account).

Water availability
The rate of transpiration and of photosynthesis of the crop are dependent on the soil (water) suction on the one hand, and on the evaporative demand of the atmosphere on the other hand. When water is in shortage, soil suction increases and the plants close their stomata in order to prevent desiccation. When the stomata's close, the uptake of CO_2 from the atmosphere is reduced and thus absorbed light is used less efficiently. This is formulated in the model by considering that the ratio of the actual transpiration, T_a (mm d^{-1}), over the potential transpiration, i.e. without water stress, T_p (mm d^{-1}), is a measure of the reduction of stomatal conductance and thus also of the reduction of photosynthesis and the light utilisation efficiency.

The factors light intensity, temperature and water stress are considered to have a multiplicative effect on maximum light utilisation efficiency, E_{max}, to result in the actual value, E_t:

$E_t = T_a/T_p$ f(T) f(PAR) E_{max} (g MJ^{-1}) (2.5)

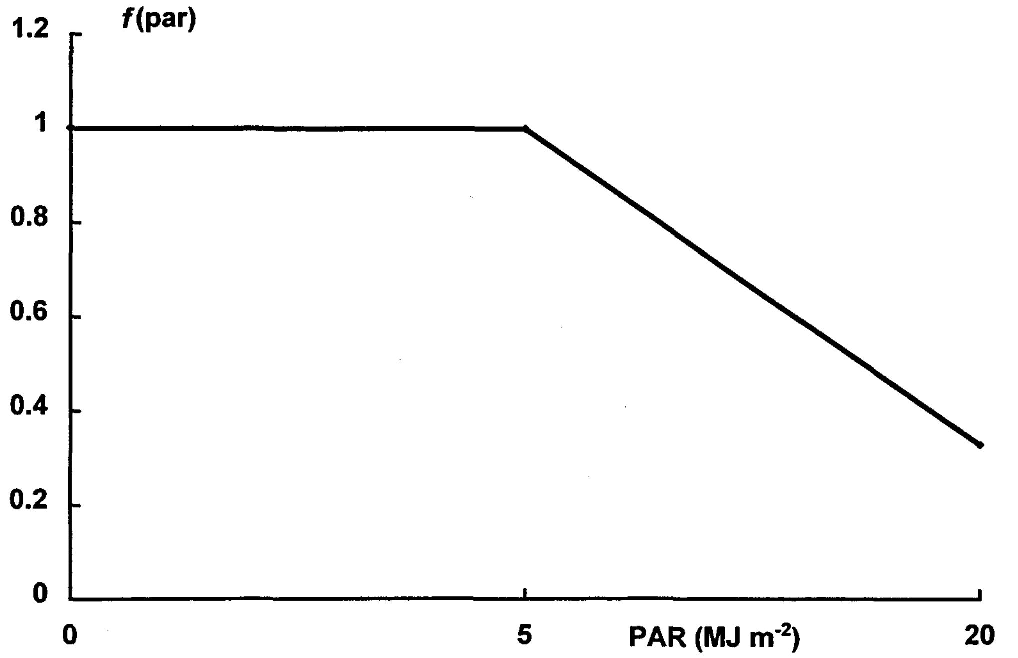

Figure 2.1 Multiplication factor on the light utilisation efficiency related to incoming PAR

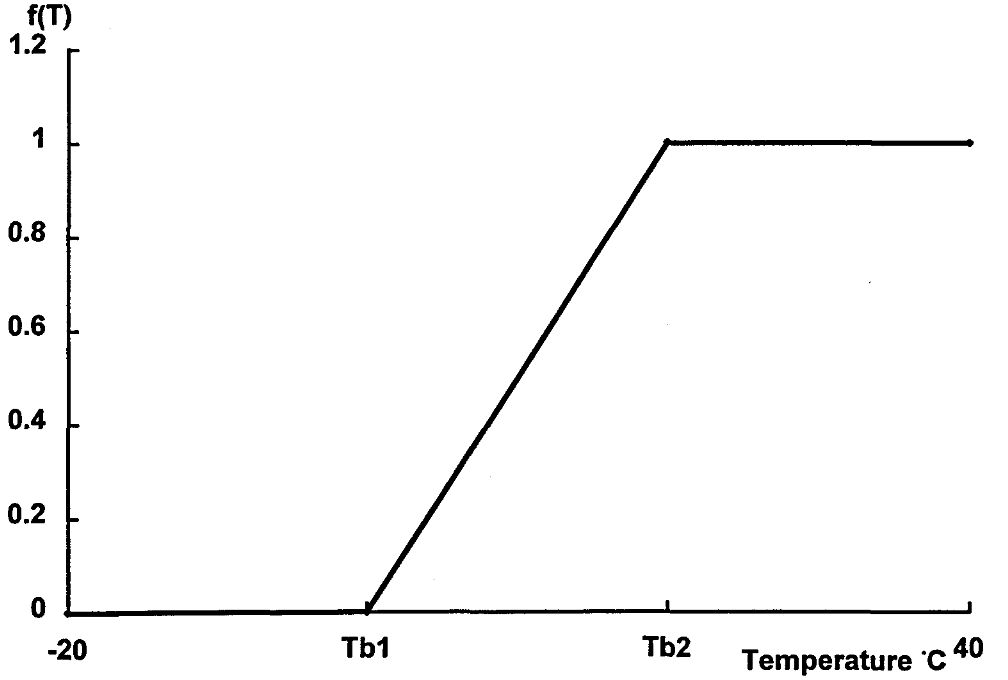

Figure 2.2 Multiplication factor on light utilisation efficiency as a function of temperature

2.3.5 Sink and source interaction

Total actual crop growth, ΔW (g d^{-1}), is determined by the balance between assimilate demand (sink), ΔW_d, and assimilate supply (source), ΔW_s. In the following, the subscript 'd' denotes the demand function, and the subscript 's' denotes the supply function.

Assimilate demand

The main demand for assimilates comes from the growing leaves since leaf growth (after cutting) is crucial for the overall productivity of grasses because it dictates the amount of light that will be absorbed during the growth period. Initial, sink-limited, leaf growth is not limited by the supply of assimilates but by temperature. In LINGRA, initial growth of leaf area after cutting is described as the product of the number of tillers after cutting that have a node for leaf elongation, TIL_n (tillers m^{-2}), the average width of new leaves, D_{lv} (m), and the leaf elongation rate ΔLV (m tiller^{-1} d^{-1}):

$$\Delta LAI_d = TIL_n \, D_{lv} \, \Delta LV \text{ (m}^2 \text{ leaf surface m}^{-2} \text{ ground surface d}^{-1}\text{)} \quad (2.6)$$

The number of tillers is determined from a special tiller routine (Paragraph 2.3.7); the average width of new leaves is a model parameter (i.e. 0.03 m), and the leaf elongation rate is described as a function of temperature, T (°C), (Spitters & Schapendonk, 1990):

$$\Delta LV = 0,.0001 \, (\ln(T) - 0.8924) \text{ (m}^2 \text{ leaf surface m}^{-2} \text{ ground surface d}^{-1}\text{)} \quad (2.7)$$

When $Tb_1 < T$ otherwise $\Delta LV = 0$

In terms of biomass, sink limited leaf growth is calculated as

$$\Delta Wl_{v,d} = \Delta LAI_d \,/\, \Delta SLA \text{ (g m}^{-2} \text{ d}^{-1}\text{)} \quad (2.8)$$

where ΔSLA is the specific leaf weight of the newly formed leaves (m^2 leaf surface m^{-2} ground surface g^{-1}).

Newly formed assimilates available for growth are partitioned between the leaves (above-ground biomass) and the roots (below-ground biomass). This partitioning between leaves and roots is independent from whether the growth is sink limited or source limited. Therefore, the total assimilate demand for (sink-limited) crop growth, ΔW_d is:

$$\Delta W_d = \Delta Wl_{v,d} \,/\, f(lv) = (\Delta LAI_d \,/\, \Delta SLA) / f(lv) \text{ (g m}^{-2} \text{ d}^{-1}\text{)} \quad (2.9)$$

where $f(lv)$ is the fraction of assimilates that is partitioned to the leaves (-).

Assimilate supply

There are two sources of assimilate supply: the amount of assimilates fixed by photosynthesis during the day, P, and the reallocated assimilates from the amount of carbohydrates stored in the reserve pool (i.e. stubble), ΔW_{pool} (g).

$$\Delta W_s = P + \Delta W_{pool} \text{ (g m}^{-2} \text{ d}^{-1}\text{)} \quad (2.10)$$

The daily rate of photosynthesis is calculated as:

$$P = E_t\ PARint = PARint\ T_a/T_p\ \ f(T)\ \ f(PAR)\ \ E_{max}\ (g\ m^{-2}\ d^{-1}) \qquad (2.11)$$

The amount of assimilates that is available for reallocation from the reserve pool is derived from the available amount and the balance between daily assimilate demand and supply (see below).

Actual growth rate
Actual total crop growth rate, ΔW, is the minimum of the assimilate demand and the assimilate supply:

$$\Delta W = \text{minimum}(\Delta W_d\ , \Delta W_s)\ (g\ m^{-2}d^{-1}) \qquad (2.12)$$

Thus, growth takes only place when the supply (photosynthesis plus reallocation from the reserve pool) exceeds or equals the demand function. Conversely, carbohydrates will be stored in the reserve pool when the photosynthetic supply exceeds the demand:

$$\Delta W_{pool}\ =\ \Delta W_s - \Delta W_d\ (g\ m^{-2}d^{-1}) \qquad \{\text{ when } \Delta W_s > \Delta W_{d}\} \qquad (2.13)$$

In general, the carbohydrate demand will be relatively high during the first days after defoliation because photosynthesis is low and the crop requires carbohydrates for regrowth of the leaves.

2.3.6 Leaf growth

Actual leaf growth is derived from the amount of assimilates available for growth and the death rate of leaves by senescence. The increase in leaf area from assimilate availability is calculated from the actual daily crop growth rate (see Paragraph 2.3.4). Net leaf growth, ΔLAI (m^2 leaves m^{-2} surface d^{-1}), is therefore:

$$\Delta LAI =\ f(lv)\ \Delta W\ \Delta SLA - \Delta DLAI\ (m^2 \text{ leaf surface } m^{-2} \text{ground surface } d^{-1}) \qquad (2.14)$$

The death rate of leaves is calculated from a relative death rate, RDR (d^{-1}):

$$\Delta DLAI = LAI\ (1\text{-}e^{(-RDR\ t)})\ (m^2 \text{ leaf surface } m^{-2} \text{ground surface } d^{-1}) \qquad (2.15)$$

where t = time (d).

The relative death rate of leaves is affected by internal shading and by water stress (Spitters & Schapendonk, 1990).

Shading
With increasing LAI, the deeper layers of the crop become shaded. The low light intensities initiate remobilisation of nitrogen from the shaded leaves and these leaves go through a stage of rapid senescence. The variation of the magnitude of relative death rate of leaves due to internal shading, RDR_{lsh} (d^{-1}), as function of LAI is given in Figure 2.3.

Water availability
Senescence is also promoted by water shortage, probably by hormonal interactions. The variation of the magnitude of relative death rate of leaves due to water shortage, RDR_{lsh} (d^{-1}), as function of the ratio of actual over potential transpiration, T_a/T_p, is given in Figure 2.4.

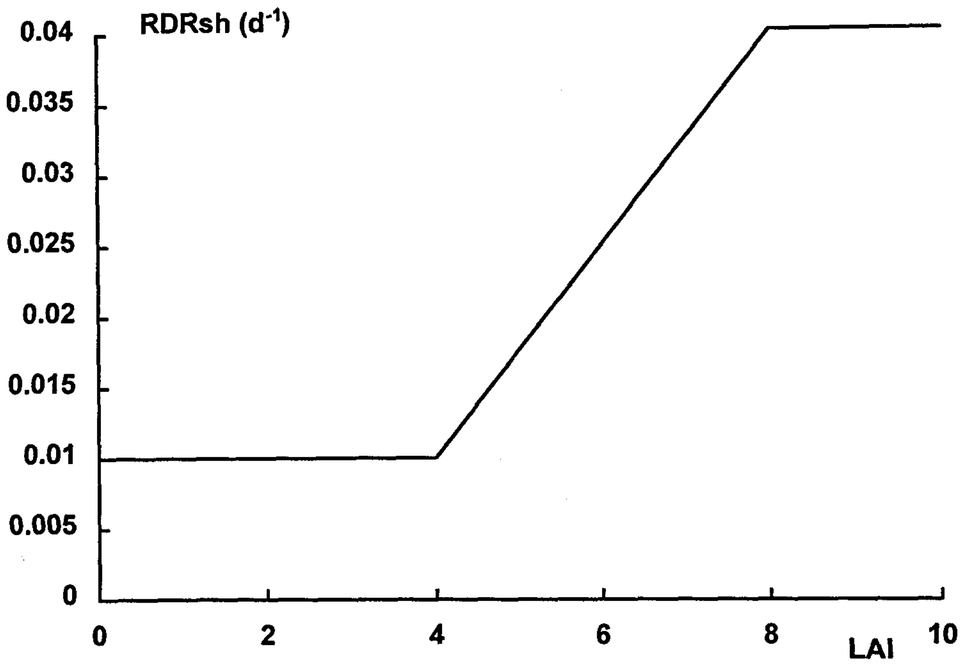

Figure 2.3. Relative death rate of leaves due to internal shading as a function of LAI.

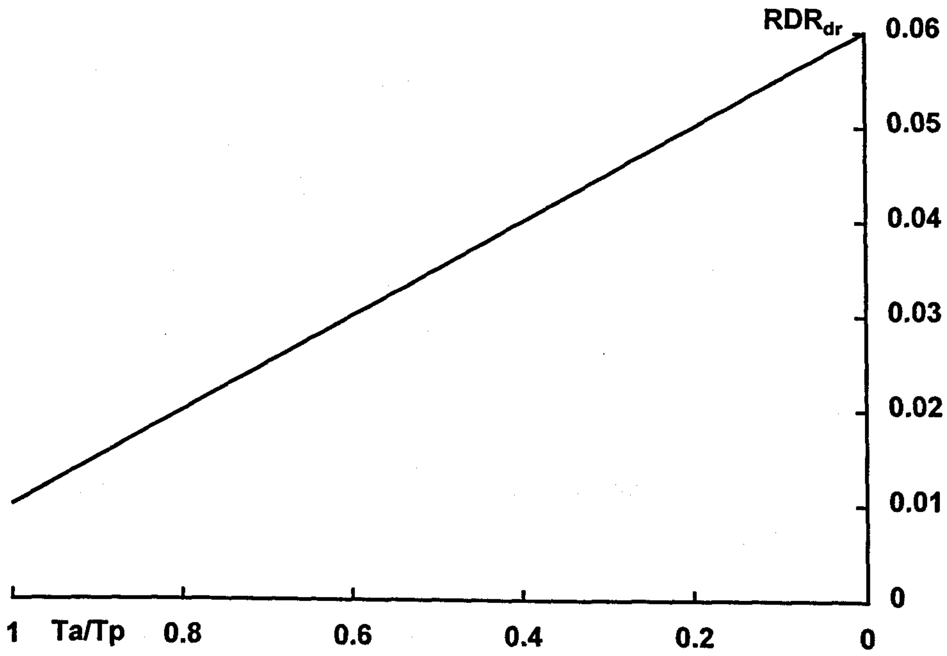

Figure 2.4. Relative death rate of leaves due to water shortage as a function of the ratio T_a/T_p.

The total relative death rate of leaves is calculated as the sum of a basis death rate and a death rate caused by internal shading and water shortage. The basic relative death rate is 0.01 (d^{-1}). The effects of internal shading and water shortage are not additive, and the overall effect is taken to be the maximum value of RDR_{sh} and RDR_{dr}. Total RDR is thus calculated as:

$$RDR = 0.01 + \text{maximum}\ (RDR_{sh}, RDR_{dr})\ (m^2 \text{ leaf surface } m^{-2} \text{ ground surface } d^{-1}) \qquad (2.16)$$

2.3.7 Tillering rate

In general there is a very close correlation between the formation of tillers and the 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. This cascade of events is sensitive to light, temperature and stress conditions. Internal shading was already mentioned as a factor that promotes senescence but it also induces tiller death and it prevents the formation of new tillers from buds.

The increase in number of tillers, ΔTIL_n (tiller m^{-2} d^{-1}), is related to the appearance rate of new leaves, $\Delta LEAF_n$, (leaf $leaf^{-1}$ d^{-1}) and to 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}):

$$\Delta TIL_n = \Delta LEAF_n\ TIL_n\ (RTR - TDR)\ (\text{tillers } m^{-2}\ d^{-1}) \qquad (2.17)$$

The appearance rate of new leaves is closely related to soil temperature. From data of Davies & Thomas (1983), a simple relation for leaf appearance rate is given by:

$$\Delta LEAF_n = Tsoil\ 0.01\ (\text{leaf } leaf^{-1}\ d^{-1}) \qquad (2.18)$$

Relative tillering rate
Relative tillering rate, RTR, is different in the first week after (periodic) cutting from the period after. In both periods, RTR is a function of LAI, modified by an effect of temperature. In the first week after cutting the relative tillering rate is given by (Van Loo, 1993):

$$RTR = (0.335 - 0.067\ LAI) * f(T)\ (\text{tiller } tiller^{-1}) \qquad (2.19)$$

where $f(T)$ is the same as the multiplication factor on light utilisation efficiency as function of temperature (Figure 2.2).

One week after cutting, RTR is calculated as:

$$RTR = (0.867 - 0.183\ LAI)\ f(T)\ (\text{tiller } tiller^{-1}) \qquad (2.20)$$

with a maximum value of 0.69.

Tiller death rate
Tiller death rate, TDR, is affected by temperature sum, Tsum (°C) and by LAI.

TDR_{Tsum} = 0.01 (1 + Tsum/600) (tiller tiller^{-1}) (2.21)
TDR_{LAI} = 0.05 (LAI - 4)/ 4 (tiller tiller^{-1}) (2.22)

The temperature sum, Tsum, is the integrated daily average temperature minus the base temperature Tb_1 (see Paragraph 3.2.1).

The effects of temperature sum and LAI are not additive, and the overall effect is taken to be the maximum value of TDR_{Tsum} and TDR_{LAI}. Total TDR is thus calculated as:

TDR = maximum (TDR_{Tsum}, TDR_{LAI}) (tiller tiller^{-1}) (2.23)

2.3.8 Transpiration

Potential evaporation and crop transpiration was calculated using the Penman formulations as implemented in subroutines of the WOFOST model (i.e. EVTRA, PENMAN; Hijmans et al., 1994; Supit et al., 1994). In the Penman formulations, potential evapotranspiration is calculated for a water surface, E_0 (cm d^{-1}), bare soil, E_{S0} (cm d^{-1}), and a reference crop, E_{T0} (cm d^{-1}), from daily weather variables (radiation, temperature, wind speed and vapour pressure). Potential transpiration of grass, E_{TC} (cm d^{-1}) is the same as that of the reference crop:

$E_{TC} = Kc\, E_{T0}$ with Kc = 1. (cm d^{-1}) (2.24)

where Kc is a crop specific correction factor on potential transpiration rate. E_{TC} is the value of potential transpiration of a crop with complete ground cover (large LAI) and with optimum supply of soil water. With incomplete ground cover, the potential transpiration rate is reduced according to its LAI (T_p):

$T_p = E_{TC}\,(1-e^{(-0.75\,Kdif\,LAI)})$ (cm d^{-1}) (2.25)

where Kdif is the extinction coefficient for total global radiation.

The transpiration rate of crops drops below the potential value when water shortage in the root zone occurs. The ratio between the actual transpiration rate, T_a, and the potential transpiration rate, T_p, is given by:

$T_a/T_p = (V_{act} - V_{wp}) / (V_{cr} - V_{wp})$ (-) (2.26)

where V_{act} is the volumetric water content in the rooting zone, V_{wp} is the volumetric soil water content where wilting begins, and V_{cr} is the critical volumetric soil water content below which transpiration decreases (see Hijmans et al., 1994; Supit et al., 1994).

The volumetric soil moisture content in the root zone is calculated by separate water balance routines that operate independent from LINGRA. In CGMS, the models WATPP and WATFD are used for potential production and water-limited production situations respectively. See Hijmans et al. (1994) and Supit et al. (1994) for details on these water balance routines.

2.3.9 Crop development

In Perennial rye grass, the crop does not fulfil a natural growth cycle such as emergence, vegetative stage, flowering, generative stage, ripening and death such as grass in the ley systems or annual crops such as cereals. The frequent cutting and/or grazing of the crop suppresses this development. Therefore, in LINGRA, no development stage is modelled that has specific relations to phenological development of the crop. To 'mimic' the simulation of crop development for comparison of earliness between different sites and seasons (and for compatibility with WOFOST), however, a development stage, DVS (-), was introduced as fraction of a temperature sum of 600 °C:

$$DVS = Tsum / 600 \ (-) \qquad (2.27)$$

where Tsum (°C) is temperature sum since the start of spring (re-)growth. A similar approach is followed to mimic a phenological development stage in WOFOST for crops such as sugar beet (Hijmans et al., 1994; Supit et al., 1994).

2.3.10 Simulated output

The output of LINGRA in CGMS as given in Table 1.1 (Paragraph 1.2.2) is related to the symbols used in the previous paragraphs as follows, Table 2.1:

Table 2.1. Relation between LINGRA output variables names in CGMS and symbols used in the scientific model description. Note: the method of calculation has been included when this was not explained in the text.

	Model abbreviation	Symbol used/ calculation
Above ground biomass	TADRW	W_{lv}
Yield	YIELD	$W_{lv} - W_{pool}$
Leaf Area Index	LAI	LAI
Development stage	DVS	DVS
Soil moisture	SM*	V_{act} *
Total water requirement	TRAMXT	$\int T_p$
Total water consumption	CTRA	$\int T_a$

*: output from water balance routine WATFD of WOFOST in CGMS (see Paragraph 2.4)

2.4 Soil water balance

The soil water balances coupled to LINGRA in CGMS are the same as used for the WOFOST model (see also Paragraph 1.2.1): WATPP for potential production and WATFD for the water-limited production situation (Hijmans et al., 1994; Supit et al., 1994).

WATPP is in fact not a true water balance since it does not keep track of water flow in a soil layer. Instead, for the simulation of crop production without water stress, WATPP consists of a statement that keeps the water content of the (rooted) soil permanently at field capacity:

$$V_{act} = V_{fc} \quad (-) \tag{2.28}$$

where V_{act} is the volumetric water content in the rooting zone, V_{fc} is the volumetric soil water content at field capacity.

WATFD is a water balance of the so-called 'tipping bucket' type, applicable to freely draining, sandy and loamy soils with a deep ground water table (> 1 m below the root zone; so that capillary rise from the ground water into the root zone does not occur). This type of soils has high hydraulic conductivity when wet, permitting fast downward water transport so that saturation of soil layers does not occur. The model can also be used for clayey soils with deeper groundwater table (> 2m below root zone), but the simulations are then more crude. The model is not suitable for (heavy) clay soils with impeded drainage. In WATFD, the water content in the soil, V_{act}, is tracked for the rooted zone with time steps of one day. Because the rooted depth is considered to be homogeneous in texture, there is no subdivision into different soil layers (1-layer model). The water balance processes considered are infiltration from precipitation (and any added irrigation water), evaporation from the surface, and water uptake by the crop (via transpiration). If rainfall intensity exceeds the maximum rate of infiltration and the surface storage capacity, water runs off. The infiltrating amount of water is added to the actual soil water content in the rooted zone, and water loss by surface evaporation and by crop transpiration is subtracted. Water can be stored in the rooted depth until field capacity is reached. Any excess water over field capacity is percolated down the rooted depth and considered as 'lost'. Upward water flow (capillary rise) is disregarded and lateral influx or outflux of water is not considered. A detailed description of the calculation statements of WATFD is given by Supit et al., 1996.

3 LINGRA parameterization and evaluation

W. Stol, B.A.M. Bouman, D.W.G. van Kraalingen & A.H.C.M. Schapendonk

3.1 Experimental data

A list was drawn of contacts of AB-DLO to be asked for experimental data of grassland suitable for model development, calibration and evaluation. This list, complemented by IRSA-JRC for East-European and Mahgreb countries, held in total 34 persons and institutions that are working in the field of grassland production and agronomy. Each of these persons or institutes were contacted by mail and asked to be involved in this project by making experimental data and developed model . code mutually available. On basis of the reactions to this enquiry, 14 more detailed requests were send. Three data sets were eventually obtained that were, in principle, suitable for model development, calibration and evaluation: one from Poland, one from Sweden and an extensive data set covering the whole of Europe that was set up by FAO. Because of the consistency with which data were collected, processed and stored in a digital data base, calibration and evaluation activities concentrated on the use of the FAO data base.

3.1.1 The FAO-database

A database with production data of grassland was produced within the framework of an FAO Subnetwork for lowland grassland by the project "Predicting production from grassland'. This project started in 1980 when a proposal submitted by Dr. A.J. Corrall of the Grassland Research Institute at Hurley, UK, was adopted by the members of this FAO Subnetwork. The aim of the project was to improve knowledge of the potential for forage production from cultivated grassland throughout the temperate climatic zone. The project was adopted by 35 members of the network, who conducted standardised experiments of grass production throughout the growing season for three to five years on sites with different climatic and soil conditions (Corrall, 1984, 1988). The resulting database contains experimental data on common grassland experiments using two standard cultivars of *Lolium Perenne* (perennial rye grass) and *Phleum pratense* (Timothy), respectively cv.'s Cropper and Kampe II, together with data on observed meteorological variables. The field experiments in their full layout included a rainfed, non-irrigated and an irrigated treatment. However, not all members of the network included both grass species and both treatments in their experiment. In the Northern countries, only Timothy was sown whereas in the Southern countries, the perennial rye grass variety was preferred. Experimental observations were conducted each year on grasslands that were newly sown in the year before. Measured crop production rates therefore hold for grasslands of a standard age, i.e. the first full harvest year. In general, the effect of ageing on grass production can be neglected since all used experimental data have the same - for forage production favourable - point of departure. For a limited number of sites, however, observations are available of both the first and the second year after sowing. Grasslands were fertilised with weekly applications following a standard procedure that was designed to ensure as far as possible that growth was never inhibited by nutrient deficiency. The experimental layout covered four harvest times on plots within the fields, in two replicates, per treatment (thus totalling 8 plots per treatment). Two plots of each treatment were periodically harvested on a four week interval from April 1st onwards till grass growth ceased in autumn. Countries in the south of Europe started somewhat earlier with the monitoring of crop production, while in the northern countries, the observations started later in the year. The original experimental observations were processed in a standardized manner before inclusion in the FAO data base. On the basis of measured data of four series of plot cuts in sequence, estimates of the weekly rate of dry matter accumulation were calculated. With this procedure, weekly and seasonal crop growth rates were derived, thus averaging out effects of timing of harvests on production of forage. This use of several series of overlapping harvesting sequences produced an annual production pattern which might be considered as the average to be expected from the harvesting sequences within a system of rotational grazing rather than a pattern unique to one specific set of harvest dates (Corrall & Fenlon, 1978; Corrall et al., 1979). Next to the processed crop variables, meteorological data were stored in the data base on weekly basis.

To enable the use of the data in the FAO-database for calibration and evaluation of the LINGRA model, a conversion program called FAOGRASS was developed to convert the experiment files in the database to files that could directly be used within the FORTRAN Simulation Environment of van Kraalingen (1995), see Paragraph 1.2.1. Weather data extracted from the database were quality checked, and, where needed, revised. An example of an experimental observation file (f3084obs.dat) and a corresponding weather data file (gbr76.984), belonging to the experiment carried out at North Wyke in the UK in 1984 is given in Appendix IV.

3.1.2 Selected data

Table 3.1 gives an overview of the experimental data of the FAO data base that were used for calibration and evaluation of LINGRA. The location of the experimental sites is given in Figure 3.1. For LINGRA, only experimental data on perennial rye grass are relevant and only these data were selected from the data base. Data of experiments that had missing observations on harvests, or that had weather data that could only be used after major revision were rejected. The same holds for data that were considered 'suspicious' because of unexplained large deviating behaviour (large variation in observed dry matter production across years while variation in measured radiation and temperature across years was small; however, only one site was rejected because of this reason). From those sites that had monitored forage production both in the first and in the second full harvest year after sowing, only the data of the first year after sowing were used.

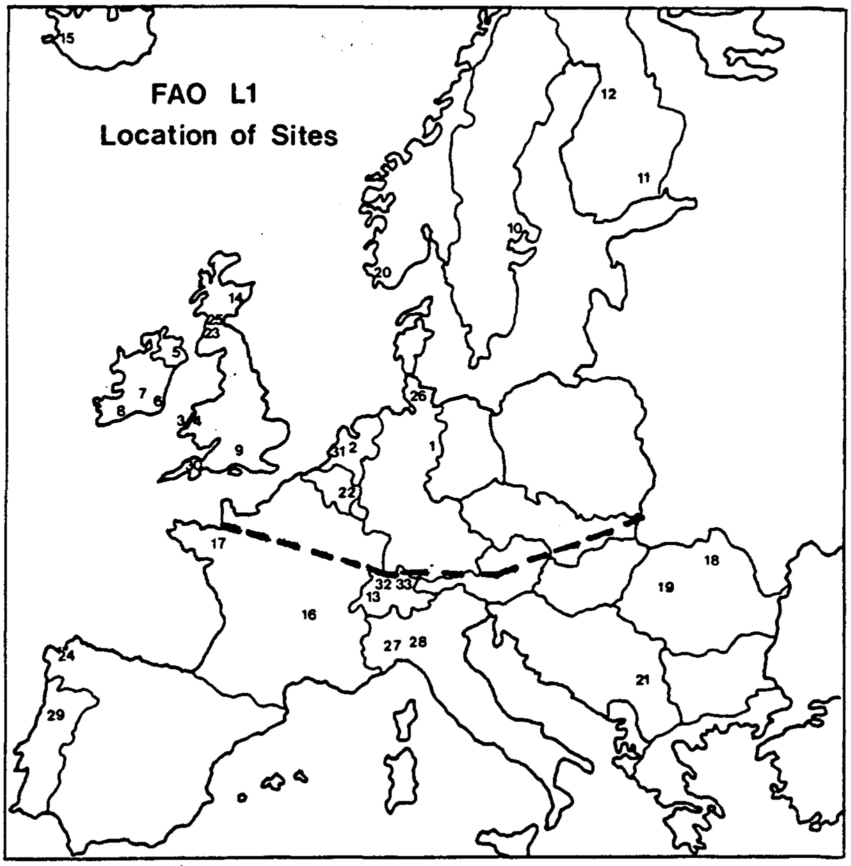

Figure 3.1. Site location of experiments in the project "Predicting production from grassland' of the FAO Subnetwork for lowland grassland, as stored in the FAO data base. The numbers of the locations correspond with the site numbers given in Table 3.1. The drawn line is the boundary between the Northern and the Southern grassland variety as derived from calibration of LINGRA (Paragraph 3.2.4)

Table 3.1. Overview of experimental data of the FAO data base that were used for calibration (marked with *) and evaluation of LINGRA.

Country	Experimental site	Site no.	Year	Final yield Irrigated (kg dm/ha)	Final yield Non-irrigated (kg dm/ha)	Data set used for Calibration
Belgium	Michamps	22	1984	12940	13000	-
Belgium	Michamps	22	1985	12770	12850	-
Eire	Grange	7	1982	-	16330	*
Eire	Grange	7	1984	-	15800	*
Eire	Moorepark	8	1982	-	16330	*
England (UK)	North Wyke	30	1983	12690	9790	-
England (UK)	North Wyke	30	1984	13670	9890	-
England (UK)	North Wyke	30	1985	11570	11610	-
France	Bourg-Lastic	16	1983	-	9630	-
France	Bourg-Lastic	16	1984	-	9350	-
France	Bourg-Lastic	16	1985	-	7745	-
France	Bourg-Lastic	16	1986	-	6210	-
France	Rennes	17	1984	15350	12970	*
France	Rennes	17	1985	13320	8930	-
Germany	Braunschweig	1	1983	-	10230	-
Germany	Braunschweig	1	1984	-	13150	-
Germany	Braunschweig	1	1985	-	9980	-
Germany	Braunschweig	1	1986	-	12760	-
Germany	Kiel	26	1984	-	14480	-
Germany	Kiel	26	1985	-	19700	-
Italy	Carmagnola	27	1983	16480	14430	*
Italy	Carmagnola	27	1984	15010	14310	-
Italy	Lodi	28	1983	14820	11880	*
Italy	Lodi	28	1984	14670	11330	-
Italy	Lodi	28	1985	12110	6970	-
N. Ireland (UK)	Crossnacreevy	5	1982	18710	17230	*
N. Ireland (UK)	Crossnacreevy	5	1983	15300	16120	*
N. Ireland (UK)	Crossnacreevy	5	1984	18240	17320	*
Netherlands	Wageningen	2	1983	15490	11430	-
Netherlands	Wageningen	2	1984	11620	10490	-
Netherlands	Zegveld	31	1984	17690	16480	*
Netherlands	Zegveld	31	1985	17800	17620	*

Table 3.1 continued.

Country	Experimental site	Site no.	Year	Final yield Irrigated (kg dm/ha)	Final yield Non-irrigated (kg dm/ha)	Dataset used for Calibration
Norway	Saerheim	20	1984	-	11220	-
Norway	Saerheim	20	1985	-	11000	-
Rumania	Cluj-Napoca	19	1986	12720	8600	*
Rumania	Suceava	18	1983	-	9640	-
Scotland (UK)	Auchincruive	23	1983	-	12960	-
Scotland (UK)	Auchincruive	23	1984	-	9830	-
Scotland (UK)	Auchincruive	23	1985	-	14160	-
Scotland (UK)	Auchincruive	23	1986	-	12300	-
Scotland (UK)	MacRobert	14	1983	-	11180	-
Scotland (UK)	MacRobert	14	1984	-	12260	-
Scotland (UK)	MacRobert	14	1985	-	16960	-
Scotland (UK)	MacRobert	14	1986	-	15010	-
Spain	La Coruna	24	1983	17569	14007	*
Spain	La Coruna	24	1984	16460	13500	-
Spain	La Coruna	24	1985	14920	12090	-
Switzerland	Changins	13	1983	14430	11870	*
Switzerland	Changins	13	1984	18910	11880	*
Switzerland	Changins	13	1985	15310	11330	-
Yugoslavia	Krusevac	21	1984	-	6520	-

3.2 Calibration

The purpose of model calibration was to find parameter values that resulted in the best fit between simulated and observed grass production at all sites across Europe. Different parameter values can be allowed for different locations in Europe when this contributes to a better match between simulations and observations at those locations. In the current version of CGMS, sets of regional-specific parameter values for arable crops as modelled with WOFOST are considered to represent different varieties, and are therefore termed 'variety parameters'. In the case of grassland as modelled with LINGRA, however, sets of different parameter values do not correspond to different varieties (since the same variety was used in the common experiments of the FAO data base), but express effects of environmental conditions that are not accounted for in the model. For compatibility between LINGRA and WOFOST, the term 'variety specific' parameter set is used here too.

European-wide calibration of LINGRA, with the provision to allow for different parameter value sets for different locations, was an interactive procedure between calibration and evaluation. The results of this calibration were 'variety' parameter sets with their geographic boundaries of applicability.

3.2.1 Calibration data

LINGRA was calibrated on the level of potential production only. The lack of information on soil characteristics and observations on the water balance of the soils during the experiments inhibited the calibration of LINGRA at the level of water-limited production. Moreover, a calibration of LINGRA at the level of water-limited production would entail a calibration of the water balance model WATFD which fell outside the scope of this project. For calibration on the level of potential production, only irrigated treatments were selected and non-irrigated treatments where rainfall was sufficient to ensure non-stressed growth (i.e. the Eire and N. Ireland sets in Table 3.1).To simulate the theoretical level of potential production, only data sets were accepted from experiments that approached unrestrained growth. In total 15 experiments were selected that showed seasonal dry matter yields close to or above 15-16 ton dry matter per hectare (Table 3.1), with the exception of Cluj-Napoca in Rumania and Changins in Switzerland that had lower yield levels. Considering the mowing interval of four weeks, it may be assumed that these crops were grown under near potential production situation (Baan-Hofman, personal communication). By selection of the water-balance WATPP that keeps the soil moisture content at optimum levels for crop growth during the whole growing season (Hijmans et al., 1994; Supit et al., 1994), no drought stress conditions occurred during simulation with LINGRA.

The subset for calibration was selected in such a manner that a sufficiently large set remained for independent evaluation of the (calibrated) model (Paragraph 3.3).

3.2.2 Model parameters for calibration

From model evaluation and sensitivity analysis, four parameters were selected for calibration (Table 3.2):

Table 3.2. LINGRA parameters (symbol, abbreviation and explanation) used for calibration. The symbols given correspond to the ones given in the model description in Chapter 2.

Symbol	Abbreviation	Explanation
Tb_1	TMBASE1	Minimum threshold temperature for photosynthesis (°C)
Tb_1	TMBASE2	Threshold temperature after which photosynthesis reaches a maximum value (°C)
LAI_c	CLAI	Leaf area index after cutting (m^2 leaf surface m^{-2} ground surface)
E_{max}	LUEMAX	Maximum light use efficiency (g MJ^{-1})

The parameter TMBASE1 determines the moment of onset of growth of the crop. In the model, TMBASE1 acts as lower limit for dry matter accumulation. If soil temperature, estimated by the 10-day moving average day temperature (actual conditions; particular year of simulation), exceeds the value of TMBASE1, accumulation of dry matter, although still reduced by temperature (Figure 2.2; Eq. 2.6), starts. The parameter TMBASE2 determines the point where temperature does not reduce dry matter accumulation anymore (Figure 2.2). In essence, these two parameters together determine the response of intercepted radiation by the crop on dry matter accumulation in spring and autumn when temperatures are suboptimal for crop performance.

The parameter CLAI determines the leaf area index after cutting of the grass, and therewith also the remaining amount of crop biomass. Low values of CLAI (short cutting heights) increase the period of sink-limited leaf and crop growth after cutting and reduce dry matter accumulation. By adapting the value of CLAI, model behaviour can be made more or less sensitive for partial light interception after cutting.

LUEMAX, is the maximum efficiency at which intercepted photosynthetic active radiation is converted in dry matter (Eq. 2.6). Its value can be derived from the crop growth curve plotted against accumulated absorbed radiation in the phase of linear growth.

The default values for these four parameters were derived during model development using greenhouse and field experiments of AB-DLO carried out at Wageningen, The Netherlands (see also Table 3.3 below)

3.2.3 Calibration algorithm and performance criterion

To assess the goodness of fit of the model with respect to experimental data, an optimisation procedure for calibration of crop growth models has been used, called FSEOPT (Stol et al., 1992). This procedure contains a controlled random search (CRS) algorithm, adapted from Price (1976), for finding the global minimum of a function with constraints on the independent variables. The algorithm can be visualised as consisting of two parts; the first being non-iterative while the second is iterative. In the first part a number of parameter sets are generated consisting of parameter values chosen at random from biologically plausible ranges around the nominal values of the model parameters. In the second part, new parameter sets are generated which replace existing sets if the new set produces model output with a better correspondence to the experimental data than the most unfavourable existing parameter set. The optimisation procedure is repeated, either by a pre-determined number of times, or until the range of goodness of fit values is less then a pre-defined limit (Klepper & Rouse, 1991; Stol et al., 1992). The criterion for goodness of fit that is used to judge the degree of correspondence between model output and experimental data depends on the objective of the research. In this study, the objective was to determine if the LINGRA model behaves similar to reality with respect to biomass production. Observed biomass production in time was derived from integration of the weekly growth rates as stored in the FAO data base. These data were compared on a weekly basis with the model state variable YIELD, which is the sum of the already harvested amount of grass, plus the amount of dry matter already accumulated in green leaves but that have not yet been harvested (see also Chapter 2). The calibration algorithm minimised the sum of the absolute differences between YIELD and the observations of the FAO-database. The sum of absolute differences was accumulated over each experiment included in the calibration algorithm, and within the experiments over the weekly observations.

3.2.4 Results

Two 'varieties' were defined for the whole of the EC, a 'Northern' and a 'Southern' variety. Using these two parameter value sets, model simulations with LINGRA compared very well with observation for all selected sites in Europe (see also Paragraph 3.3 on evaluation). The parameter set for the Northern variety was derived from 9 experimental sites (all irrigated except for the Eire and the N. Ireland set), and that for the Southern set from 6 experimental sites (all irrigated), (see Table 3.1). The geographical boundary between the two varieties runs generally from west to east through the North of France, the South of Germany, Czechia, to the three-country border of Slovakia, Poland and Russia (Figure 3.1)

The parameter values of the two varieties are given in Table 3.3:

Table 3.3. Values of the four calibration parameters of LINGRA for the default variety, the Northern and the Southern variety for Europe as derived from calibration. The meaning of the parameters are given in Table 3.2 in Paragraph 3.2.2.

Name	Units	Default	Northern	Southern
TMBASE1	°C	6	3	5
TMBASE2	°C	9	8	9.7
CLAI	m^2 leaf surface m^{-2} ground surface	0.5	0.8	0.5
LUEMAX	g MJ^{-1}	2.8	3.0	2.4

Figures 3.2 and 3.3 give the comparison between simulated and observed time courses of grassland biomass for the calibration sets of the Northern and Southern area respectively. For quantitative assessment of the goodness-of-fit of simulated harvested product, the so-called average absolute error was calculated as mean absolute difference between weekly simulated and observed harvestable biomass:

$$\text{Average absolute error} = \Sigma(|Y_{t,sim} - Y_{t,obs}|)/n \qquad (4.1)$$

where $Y_{t,sim}$ = simulated biomass at time t; $Y_{t,obs}$ = observed biomass at time t; n = number of (weekly) observations.

Calibration of the LINGRA model for the nine Northern sites resulted in a reduction of the average absolute error with 70%, from 2352 dry matter ha^{-1} using the default values, to 695 kg dry matter ha^{-1} per hectare using the calibrated parameter set. The model performed extremely well on six of the nine data sets. At two sites, both in 1984, Zegveld, The Netherlands and Grange in Eire, a moderate result was obtained. On the experiment in Changins, Switzerland, in 1984 LINGRA consistently underestimated measured crop growth rates (due to the reduction in LINGRA of the light use efficiency under high radiation intensities).
For the Southern sites, calibration of LINGRA resulted in a reduction of the average absolute error with 58%, from 2680 dry matter ha^{-1}, to 1125 kg dry matter ha^{-1} per hectare using the calibrated parameter set.

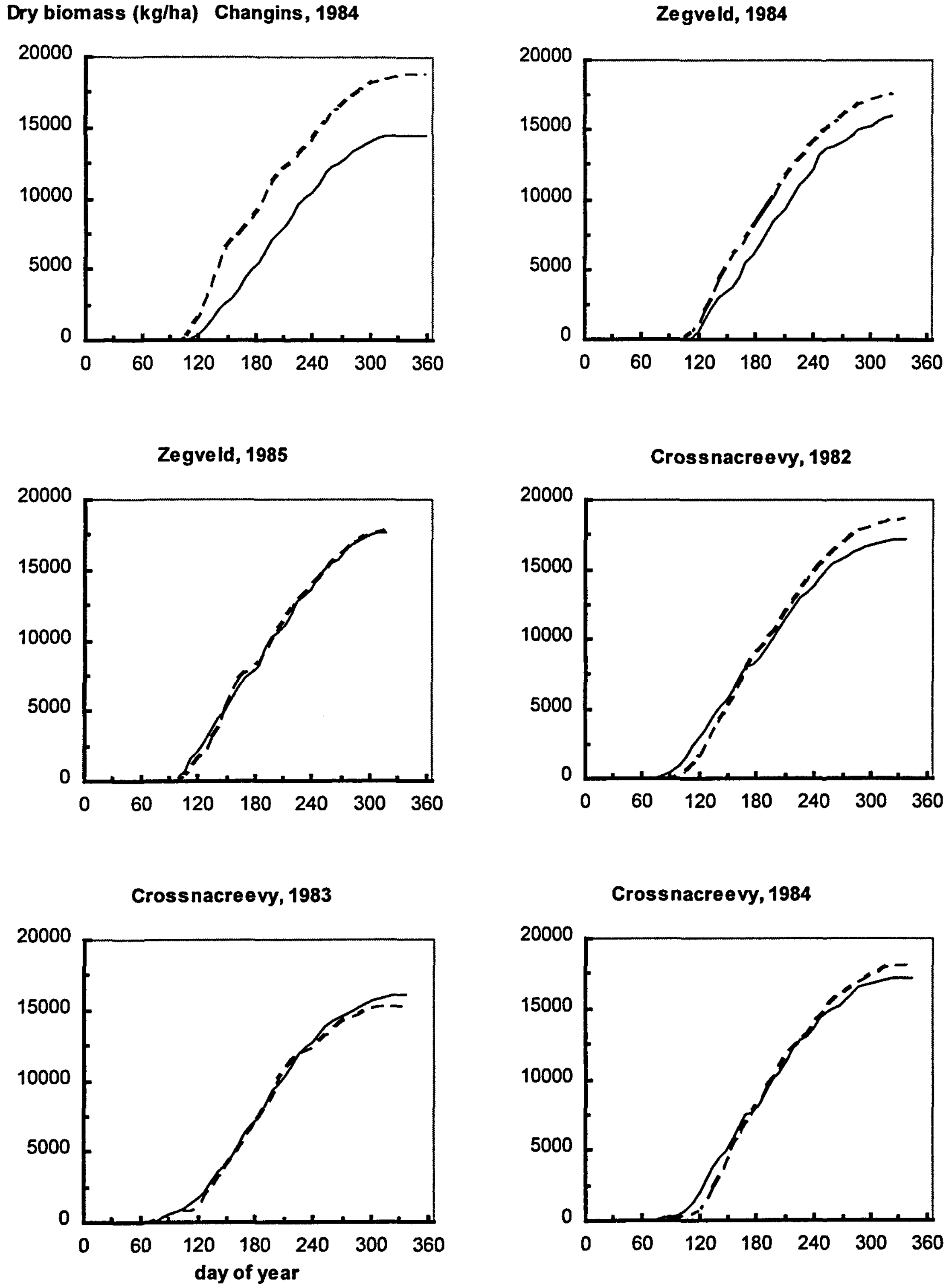

Figure 3.2. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the calibration test sites of the Northern variety. Simulations were performed for the potential production situation.

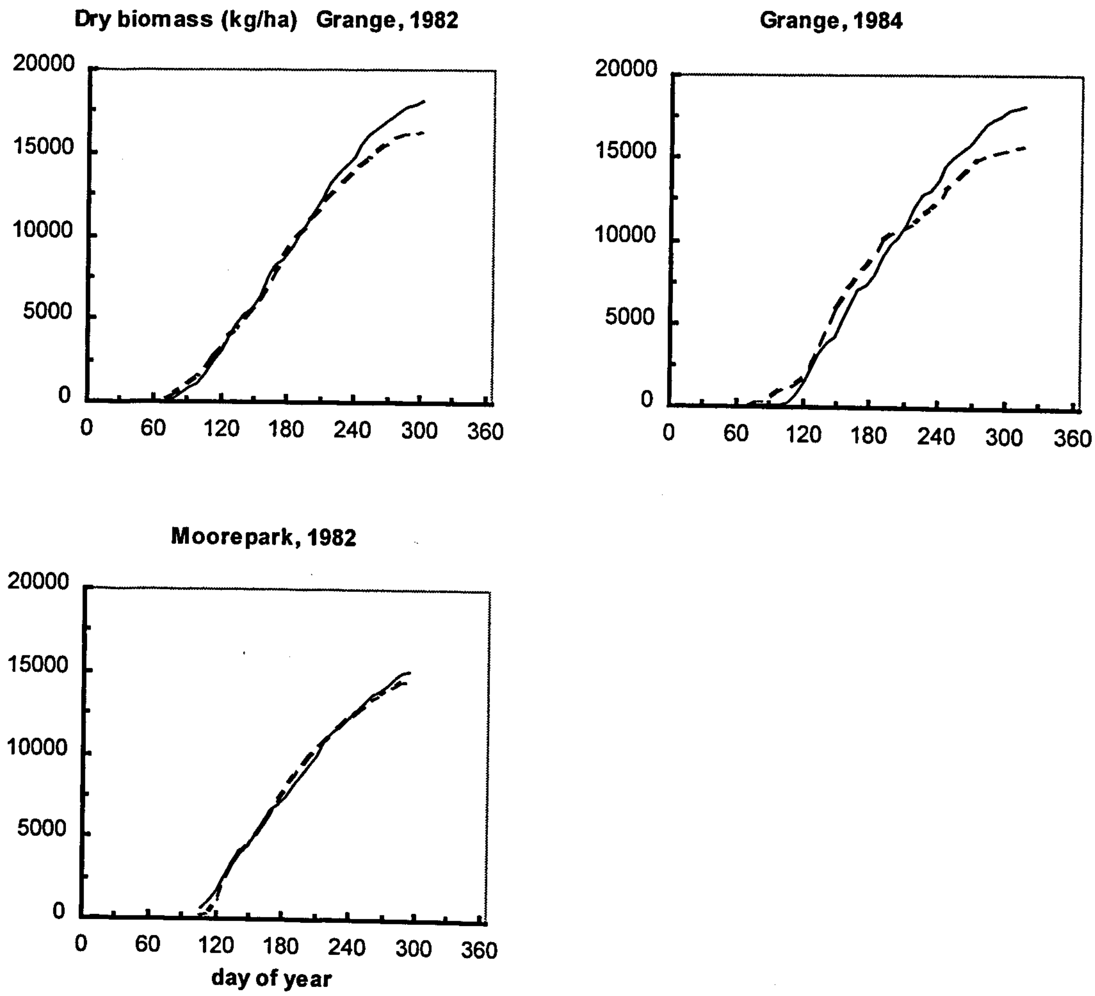

Figure 3.2. Continued. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the calibration test sites of the Northern variety. Simulations were performed for the potential production situation.

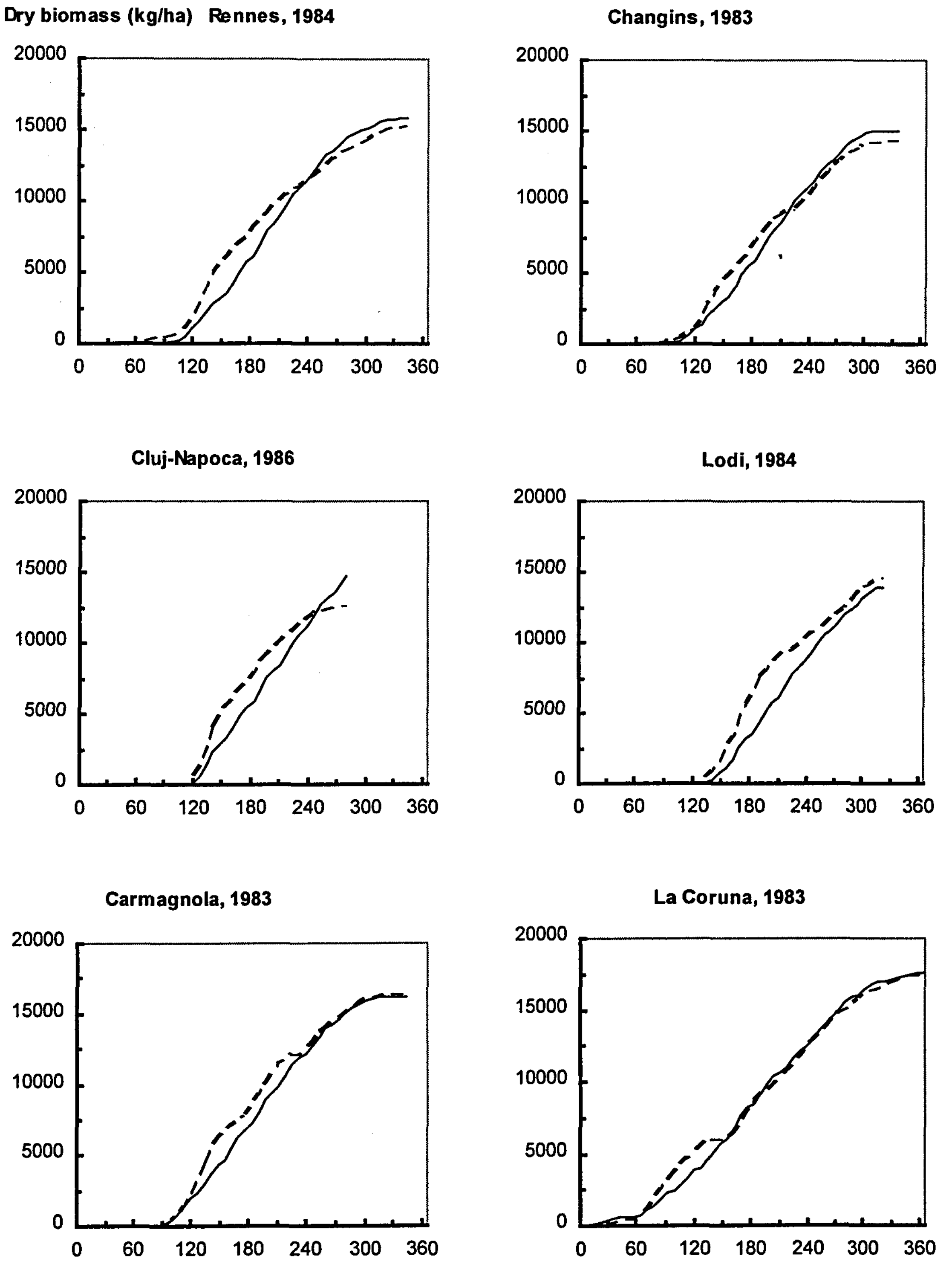

Figure 3.3. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the calibration test sites of the Southern variety. Simulations were performed for the potential production situation.

3.3 Evaluation

The performance of LINGRA was evaluated on independent data sets (i.e. those sets not used for calibration, see Table 3.1) on the level of potential production and water-limited production. For potential production, the water balance model WATPP was used that keeps the soil moisture content at optimum levels for crop growth during the whole growing season. For water-limited production, the water balance model WATFD was used for freely draining soil types. Since no actual soil characteristics for the sites were available, a standard parameter set was used for a medium textured soil type with good water-holding capacity (EC3-medium fine; Hijmans et al., 1994). Also, a standard rooting depth of 40 cm was assumed for all sites. Because of the lack of actual soil and site information, the evaluation of LINGRA at the water-limited level of production should be seen as indicative for trends only, and quite large deviations between simulations and observations can be expected.

Figures 3.4 and 3.5 give the comparison between simulated and observed time courses of grassland biomass at the level of potential production and water-limited production respectively. In general, LINGRA performed very well at the level of potential production, both for Northern and Southern sites. But also at the level of water-limited production, LINGRA performed extremely well in reproducing both trends (pattern of production in time) and absolute production levels throughout Europe. The good performance of LINGRA at the level of water-limited production is quite surprising, considering the lack of soil and site specific input data, and points to a robust behaviour of LINGRA and a high quality of the experimental data.

A quantitative assessment of the performance of LINGRA is given in Table 3.4. In this table, the average absolute error (Eq. 4.1) is given for each experimental data set of the FAO data base (see also Table 3.1).

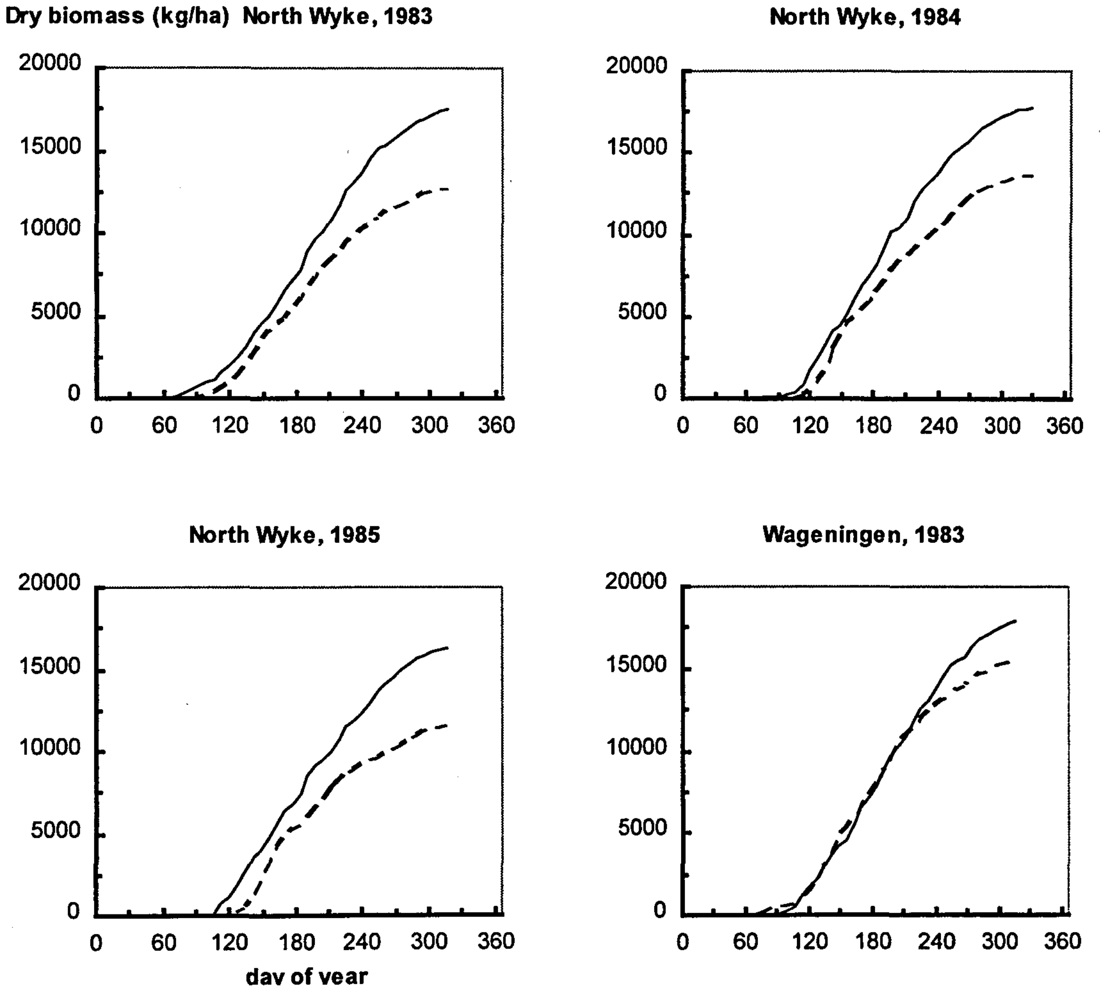

Figure 3.4. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the level of potential production; independent evaluation set.

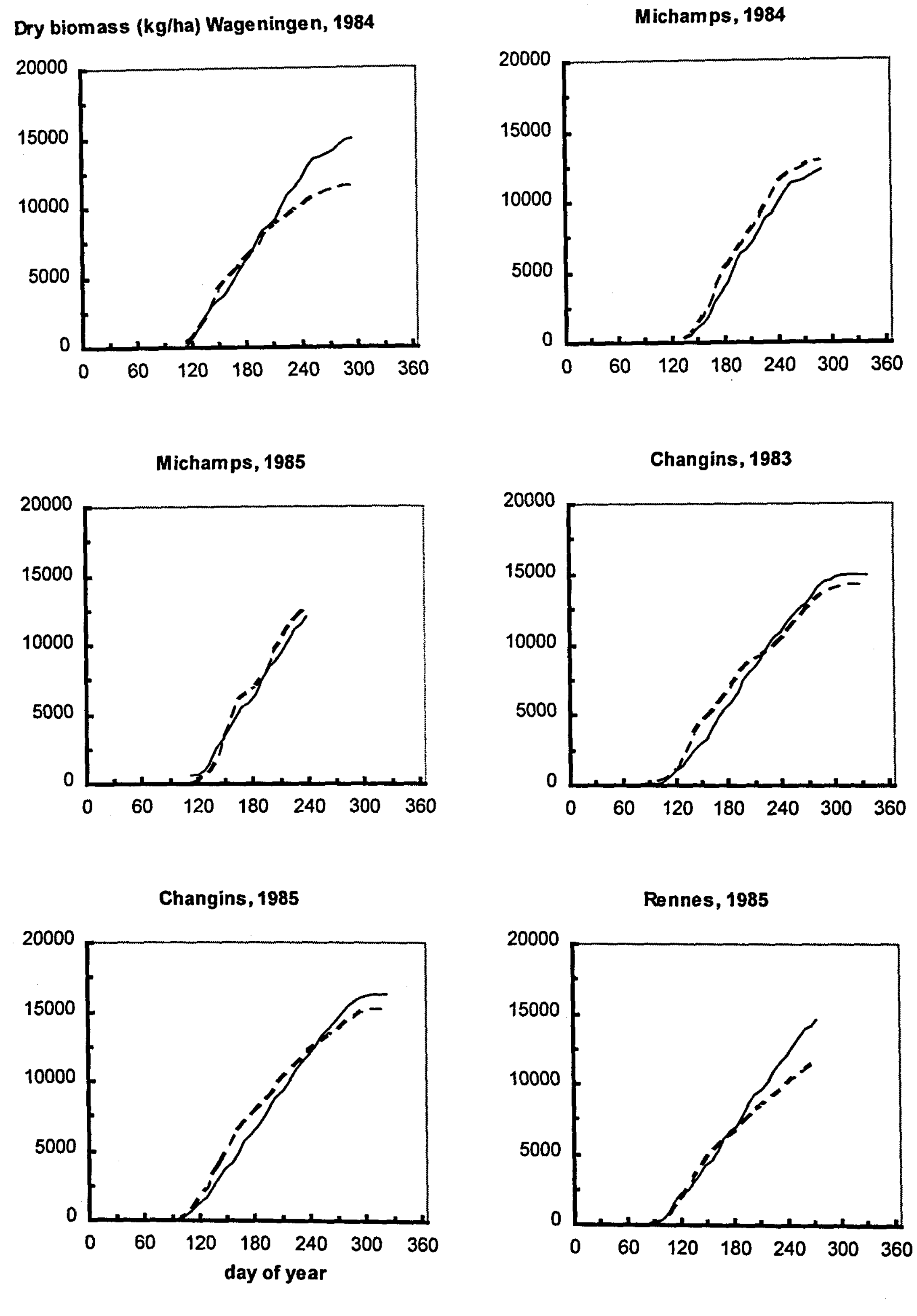

Figure 3.4. Continued. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the level of potential production; independent evaluation set.

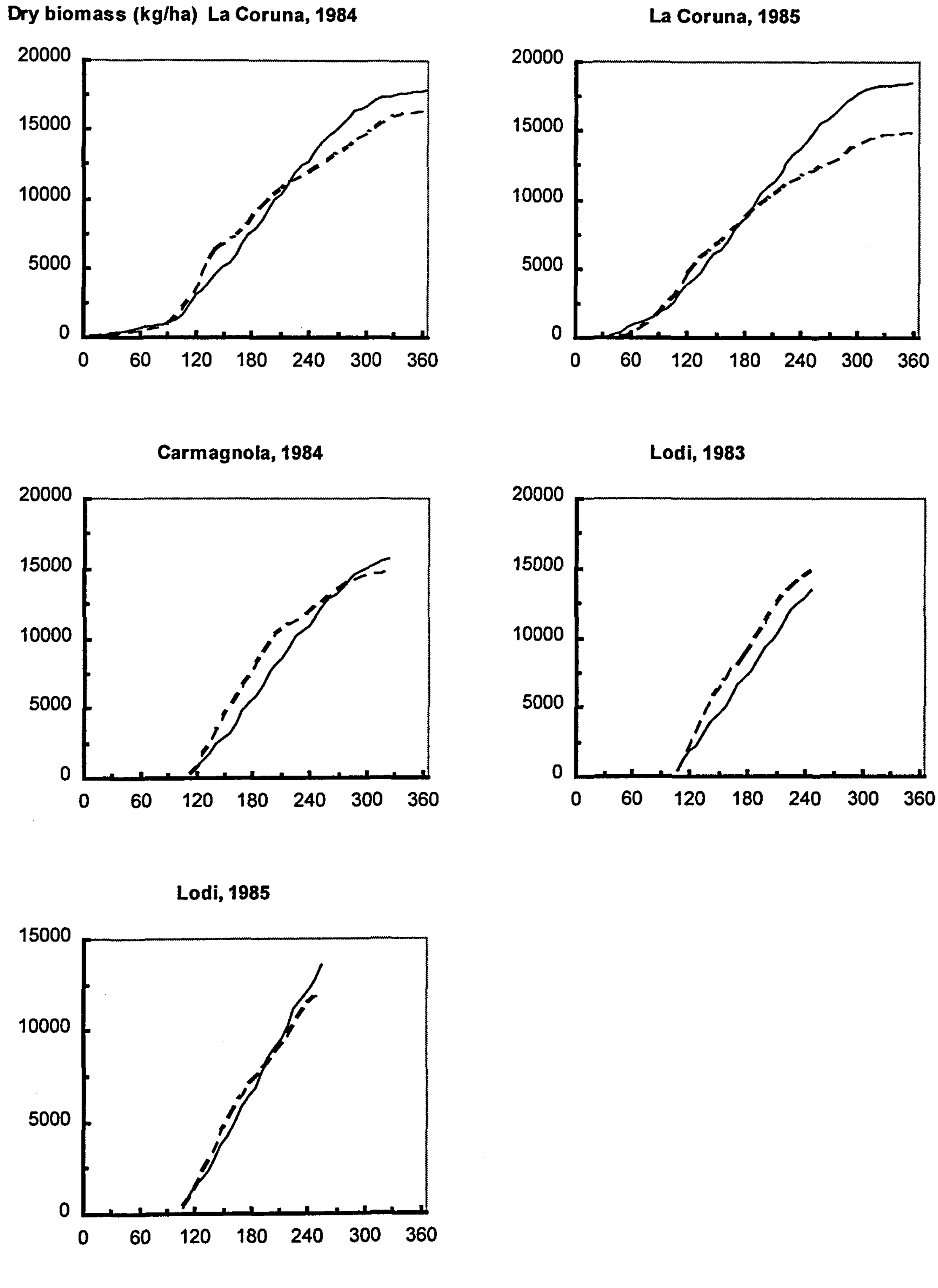

Figure 3.4. Continued. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the level of potential production; independent evaluation set.

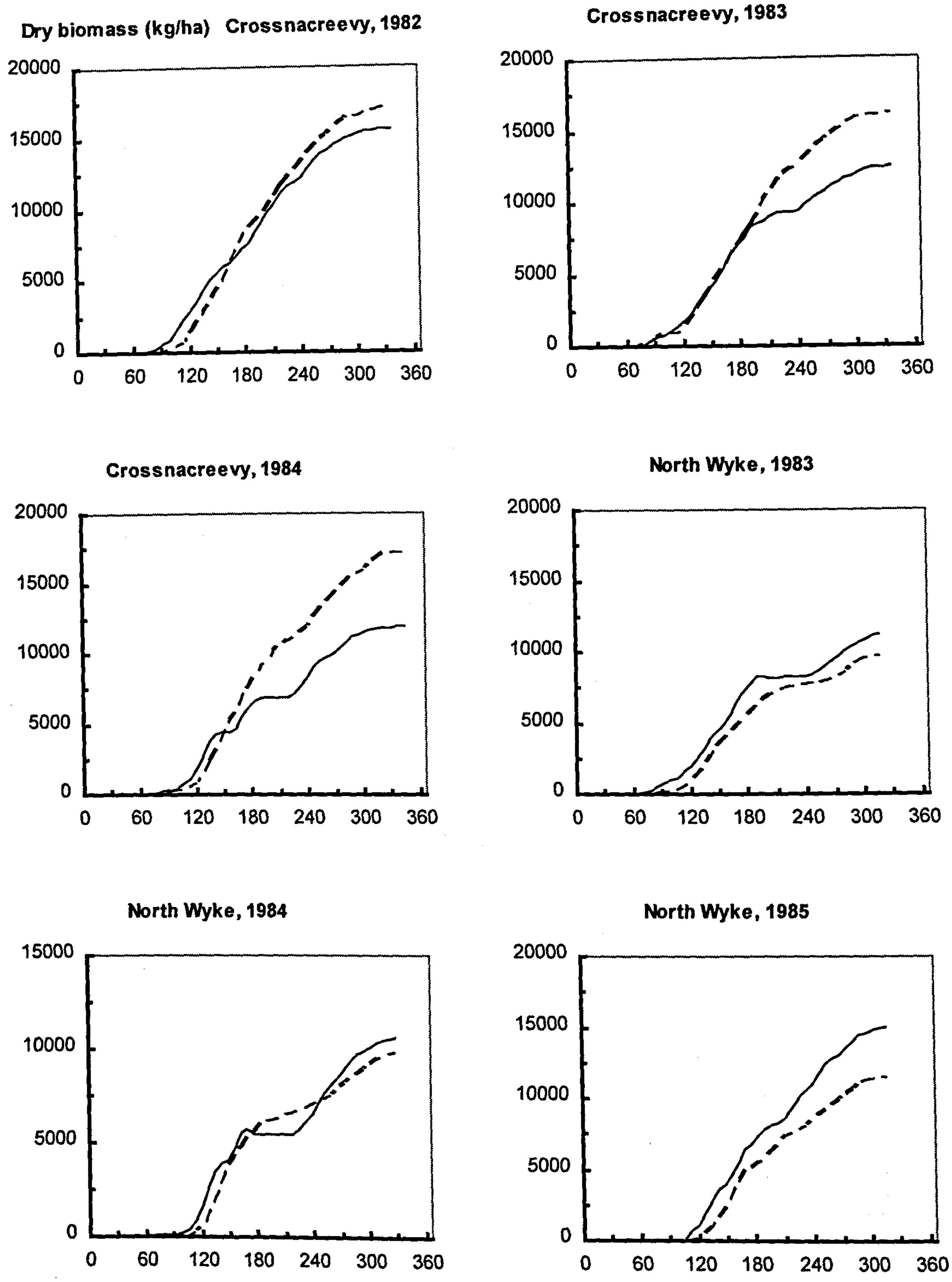

Figure 3.5. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the level of water-limited production; independent evaluation set.

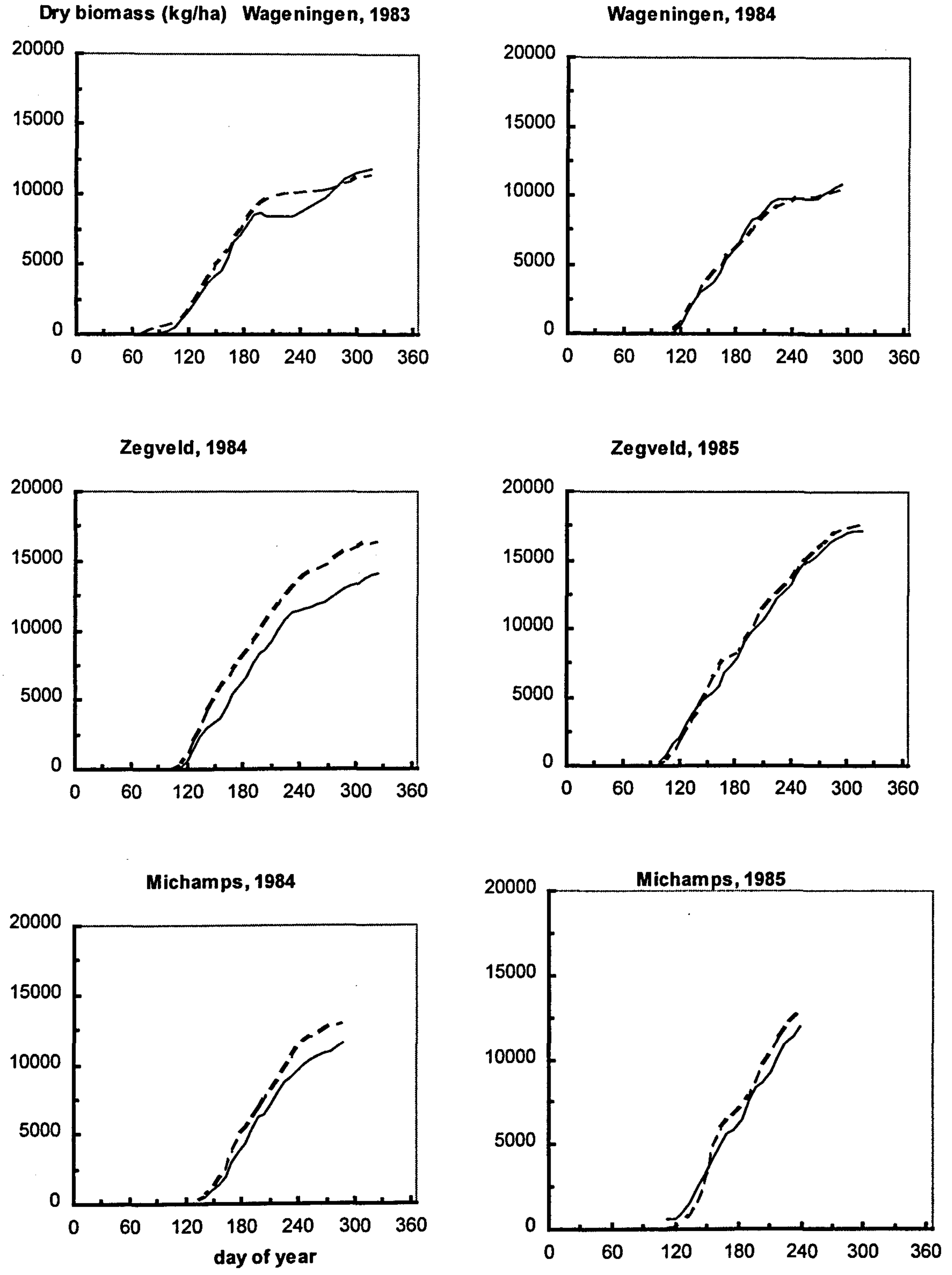

Figure 3.5. Continued. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the level of water-limited production; independent evaluation set.

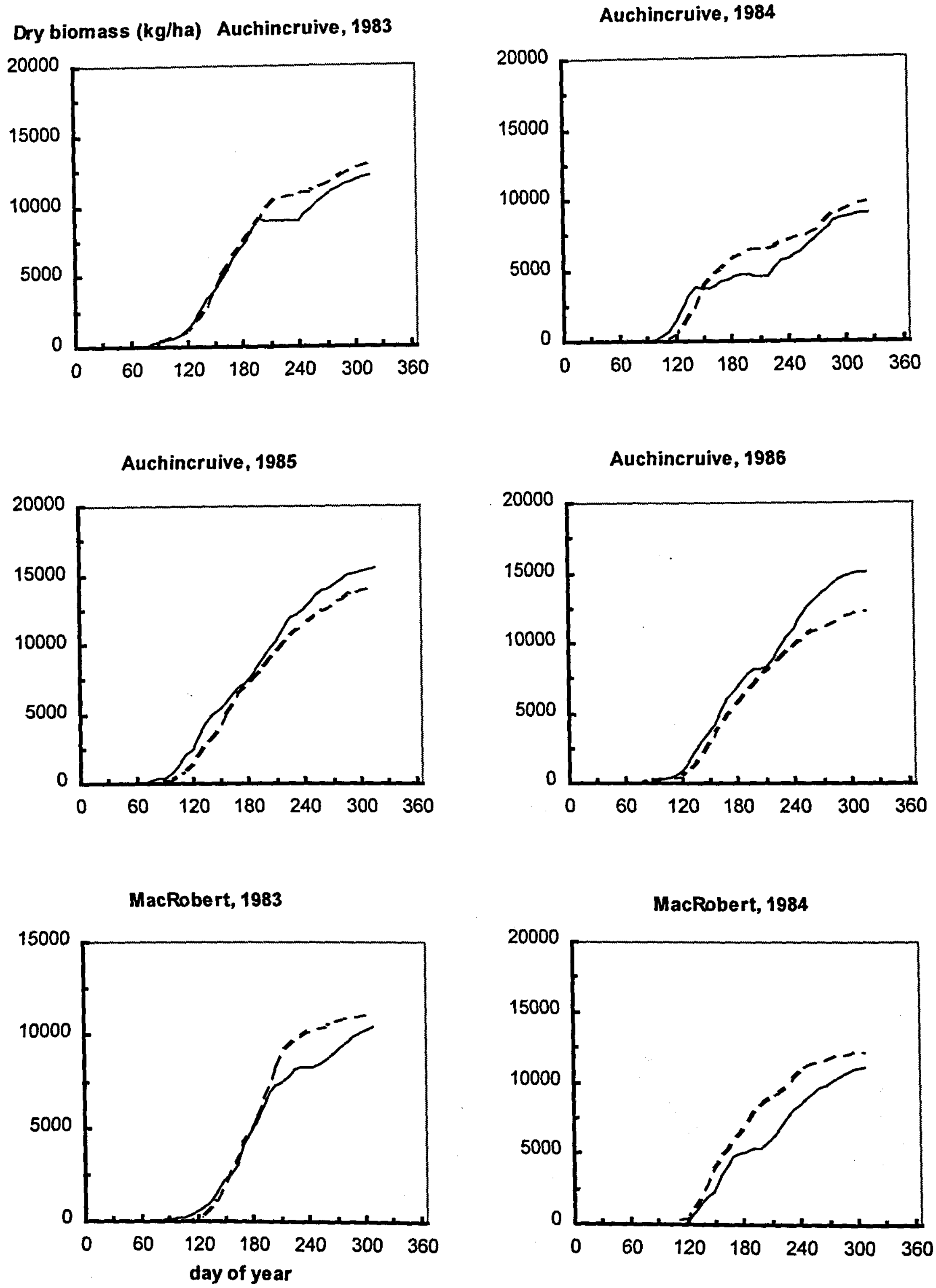

Figure 3.5. Continued. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the level of water-limited production; independent evaluation set.

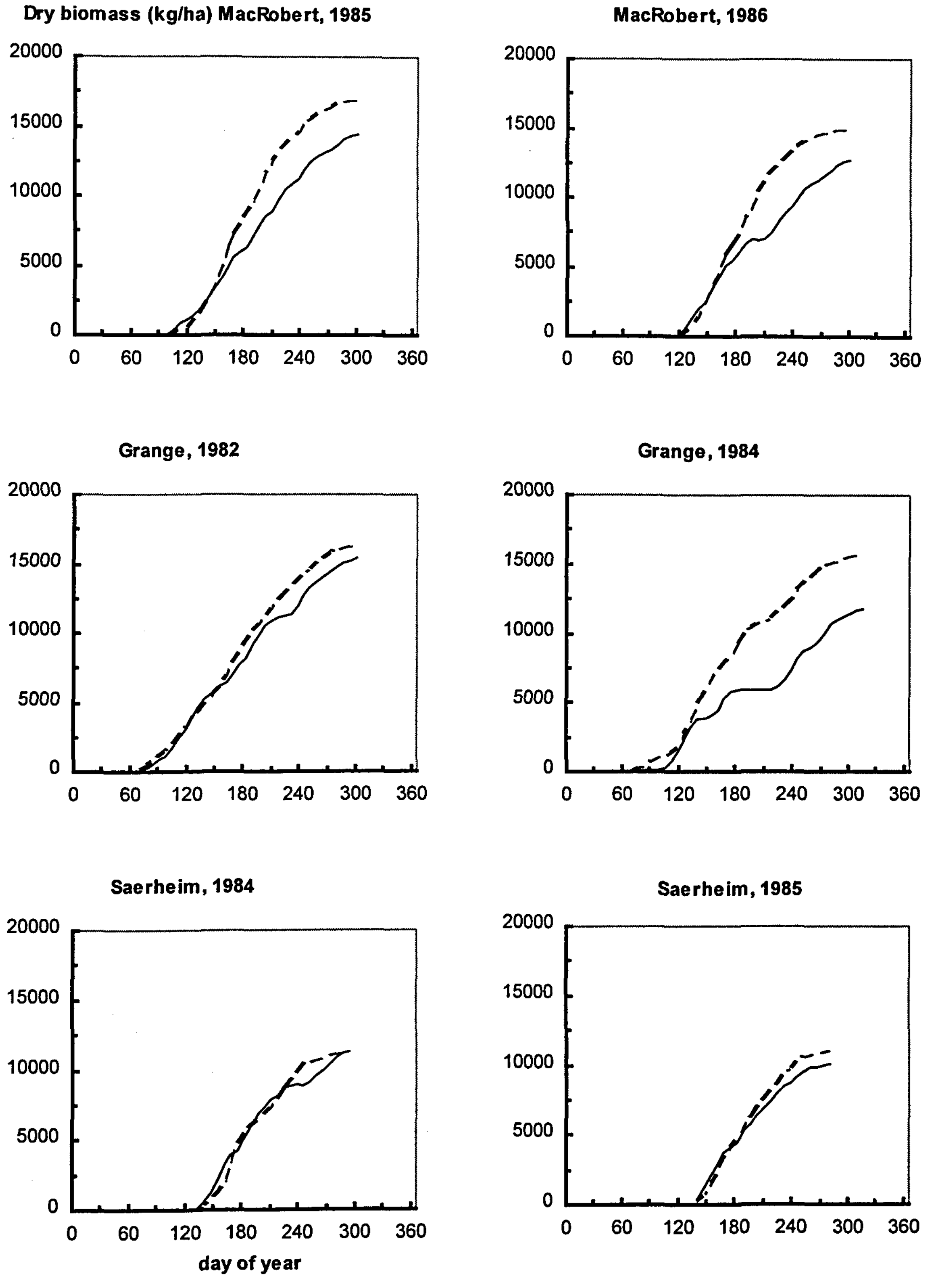

Figure 3.5. Continued. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the level of water-limited production; independent evaluation set.

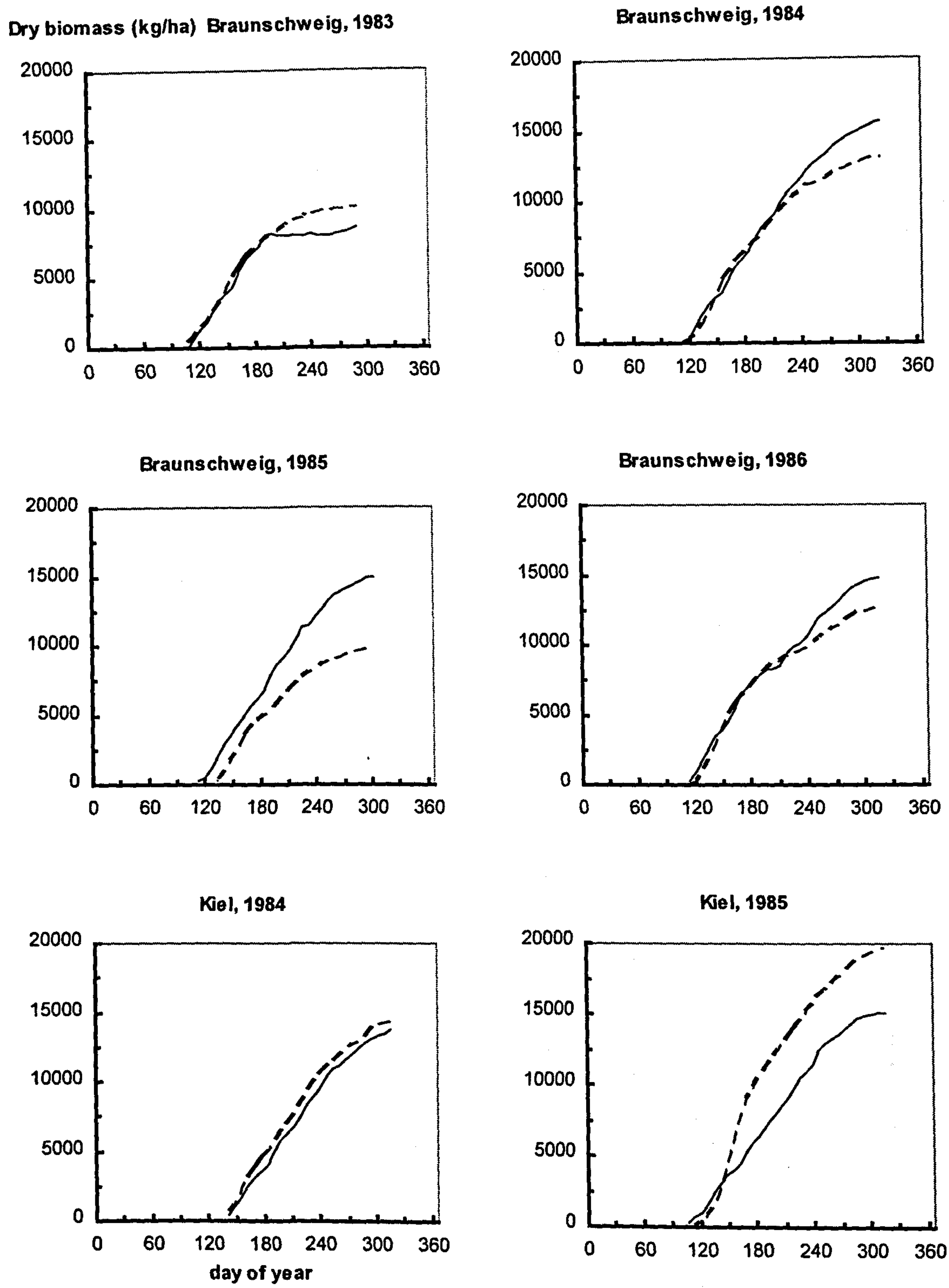

Figure 3.5. Continued. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the level of water-limited production; independent evaluation set.

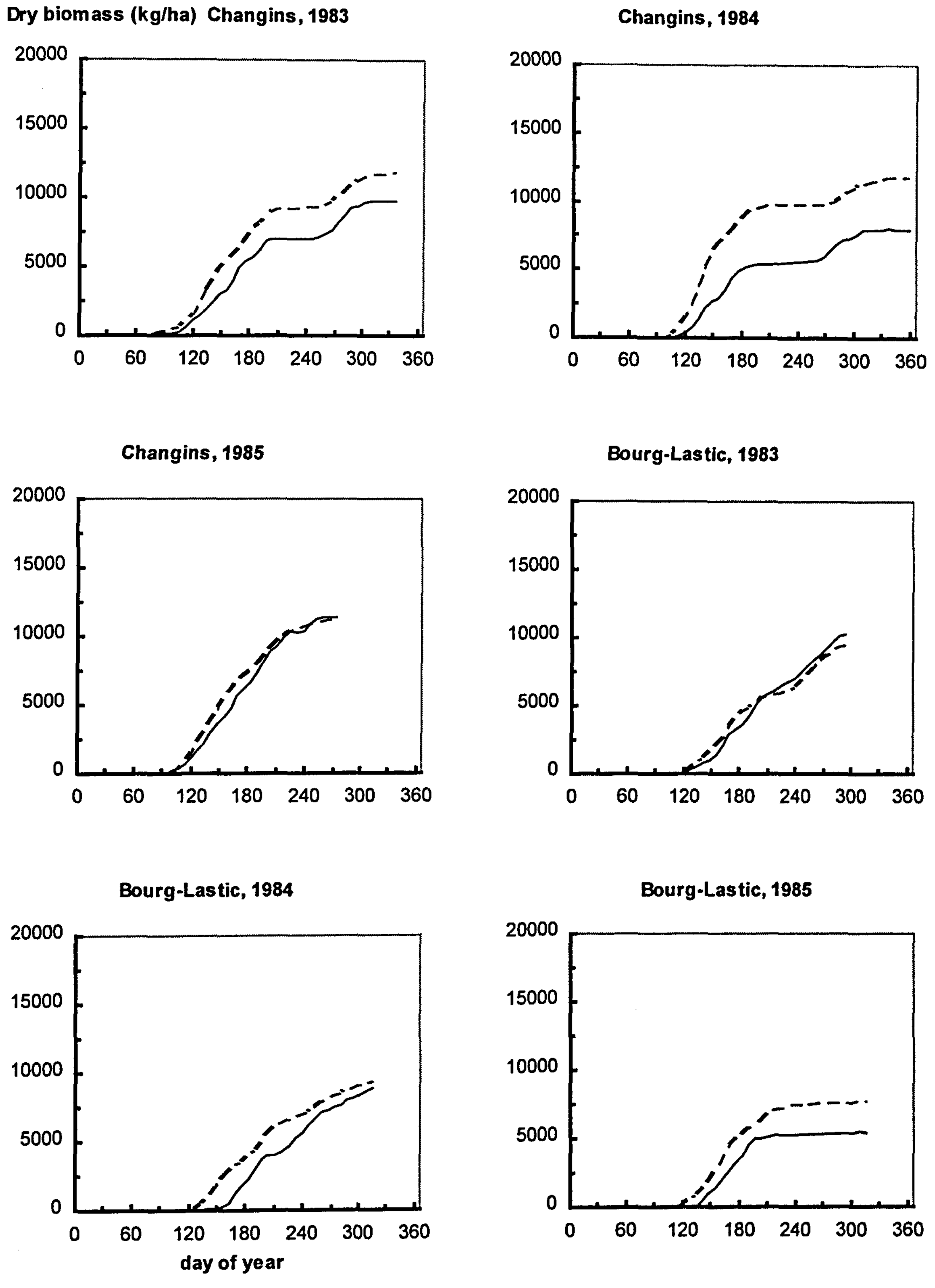

Figure 3.5. Continued. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the level of water-limited production; independent evaluation set.

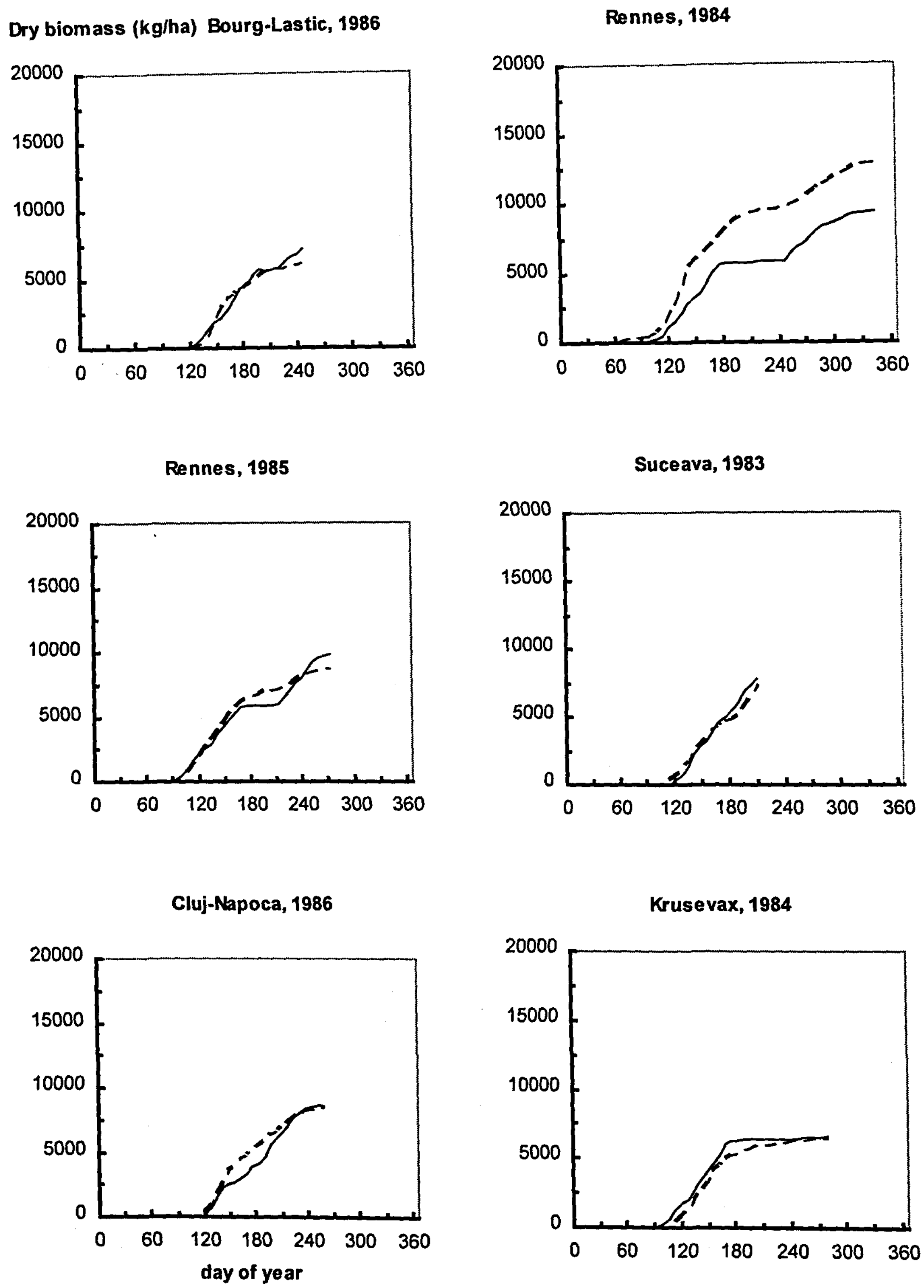

Figure 3.5. Continued. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the level of water-limited production; independent evaluation set.

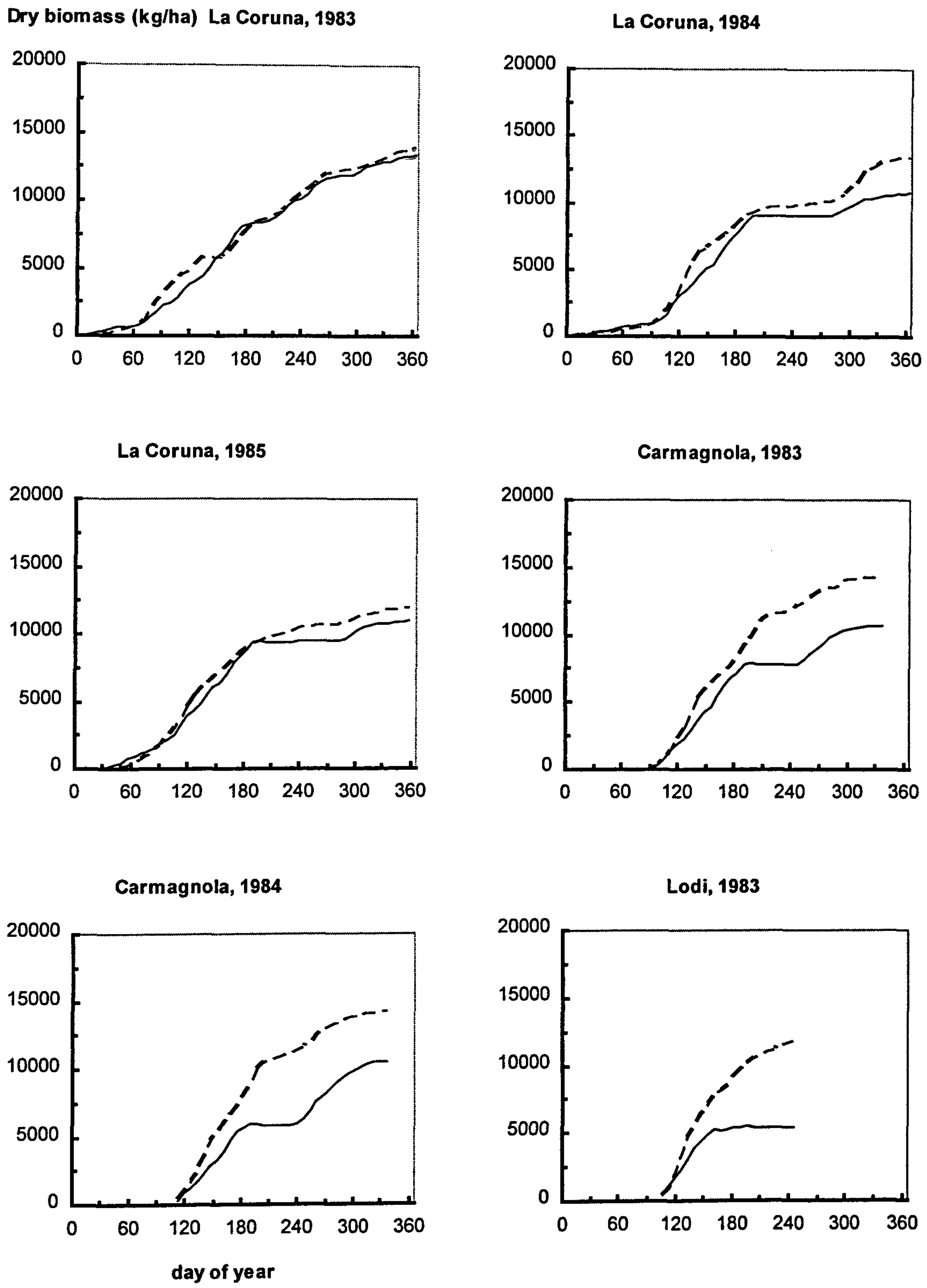

Figure 3.5. Continued. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the level of water-limited production; independent evaluation set.

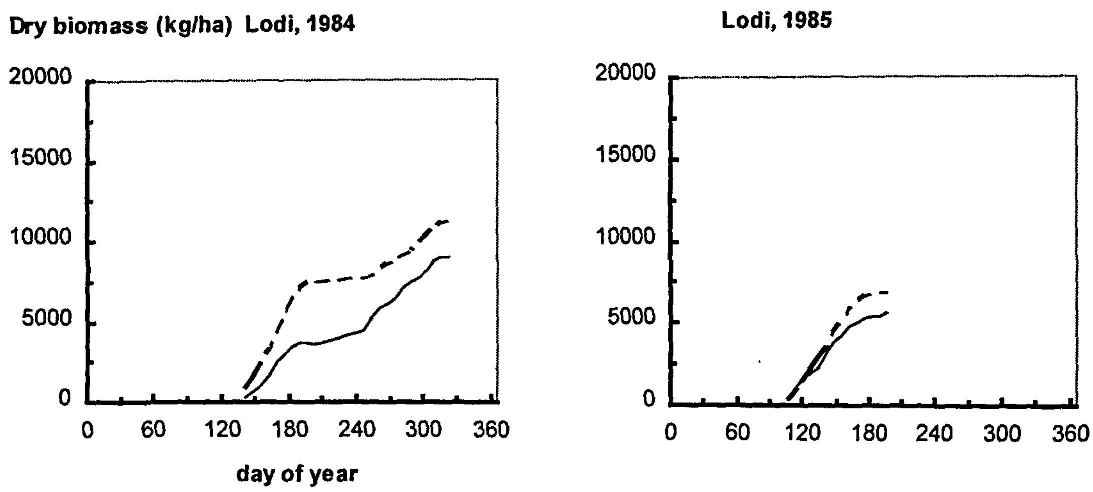

Figure 3.5. Continued. Observed (dotted line) and simulated (drawn line) production (harvestable dry matter, kg ha^{-1}) of perennial rye grass at the level of water-limited production; independent evaluation set.

Table 3.4. Average absolute error (kg dry matter ha^{-1}), calculated as mean absolute difference between weekly simulated and observed harvestable biomass, per experimental data set (see Eq. 4.1)

Country	Experimental site	Year	Avg. absolute error Irrigated (kg dm/ha)	Avg. absolute error Non-irrigated (kg dm/ha)	Data set used for Calibration
Belgium	Michamps	1984	874	1090	-
Belgium	Michamps	1985	644	761	-
Eire	Grange	1982	-	821	*
Eire	Grange	1984	-	3091	*
Eire	Moorepark	1982	-	304	*
England (UK)	North Wyke	1983	2537	1031	-
England (UK)	North Wyke	1984	2178	616	-
England (UK)	North Wyke	1985	2828	2125	-
France	Bourg-Lastic	1983	-	476	-
France	Bourg-Lastic	1984	-	1266	-
France	Bourg-Lastic	1985	-	1495	-
France	Bourg-Lastic	1986	-	365	-
France	Rennes	1984	990	2556	*
France	Rennes	1985	907	482	-
Germany	Braunschweig	1983	-	800	-
Germany	Braunschweig	1984	-	1012	-
Germany	Braunschweig	1985	-	2893	-
Germany	Braunschweig	1986	-	882	-
Germany	Kiel	1984	-	741	-
Germany	Kiel	1985	-	3262	-
Italy	Carmagnola	1983	690	2484	*
Italy	Carmagnola	1984	1050	3452	-
Italy	Lodi	1983	1508	3398	*
Italy	Lodi	1984	1461	2333	-
Italy	Lodi	1985	559	796	-
N. Ireland (UK)	Crossnacreevy	1982	836	950	*
N. Ireland (UK)	Crossnacreevy	1983	334	1726	*
N. Ireland (UK)	Crossnacreevy	1984	514	2726	*
Netherlands	Wageningen	1983	818	556	-
Netherlands	Wageningen	1984	1139	268	-
Netherlands	Zegveld	1984	1644	1892	*
Netherlands	Zegveld	1985	286	461	*
Norway	Saerheim	1984	-	558	-
Norway	Saerheim	1985	-	657	-
Rumania	Cluj-Napoca	1986	1377	639	*
Rumania	Suceava	1983	-	451	-

Table 3.4. Continued. Average absolute error (kg dry matter ha^{-1}), calculated as mean absolute difference between weekly simulated and observed harvestable biomass, per experimental data set (Eq. 4.1).

Country	Experimental site	Year	Avg. absolute error Irrigated (kg dm/ha)	Avg. absolute error Non-irrigated (kg dm/ha)	Dataset used for Calibration
Scotland (UK)	Auchincruive	1983	-	629	-
Scotland (UK)	Auchincruive	1984	-	901	-
Scotland (UK)	Auchincruive	1985	-	991	-
Scotland (UK)	Auchincruive	1986	-	2539	-
Scotland (UK)	MacRobert	1983	-	833	-
Scotland (UK)	MacRobert	1984	-	1496	-
Scotland (UK)	MacRobert	1985	-	2076	-
Scotland (UK)	MacRobert	1986	-	2269	-
Spain	La Coruna	1983	405	422	*
Spain	La Coruna	1984	957	965	-
Spain	La Coruna	1985	1488	647	-
Switzerland	Changins	1983	658	1599	*
Switzerland	Changins	1984	3534	3244	*
Switzerland	Changins	1985	799	495	-
Yugoslavia	Krusevac	1984	-	459	-

3.4 Overall evaluation and conclusion

Table 3.5 lists average absolute errors (Eq. 4.1) between simulated and observed biomass as mean values over all experiments for the Northern and the Southern areas in Europe. For mutual comparison, these errors were normalized to 50% of the final biomass at the end of the growing season:

$$\text{Normalized error} = 100\,\{\Sigma(|Y_{t,sim} - Y_{t,obs}|)/n\}/Y_{mean,\,obs}\ (\%) \qquad (4.2)$$

where $Y_{t,sim}$ = simulated biomass at time t; $Y_{t,obs}$ = observed biomass at time t; $Y_{mean,\,obs}$ = 50% of observed biomass at the end of the growing season; n = number of (weekly) observations.

From Table 3.5, it is seen that the normalized simulation error was about the same for the Northern and Southern sites on the level of potential production. The normalized errors were higher at the level of water-limited production because of the lack of soil and site input data (see Paragraph 3.3). Overall, the values are between 13-21%, which is a very good peformance for crop growth simulation models (Loomis et al., 1979; Penning de Vries, 1983; Bouman et al., 1996).

Figure 3.6 Gives the comparison of simulated total harvested product at the end of the growing season with observed values for the whole data set on the level of potential production (3.6a) and water-limited production (3.6b).

It is concluded that LINGRA performed well in predicting observed grassland production of perennial rye grass experiments throughout Europe, both on the level of potential and water-limited production. Simulated time trends and absolute levels of production matched observed ones well.

Table 3.5. Average absolute error (Eq. 4.1) and normalized absolute error (Eq. 4.2) between LINGRA predictions of harvestable biomass and observed values, as mean values for the Northern and Southern variety areas in Europe. For comparison, the mean of the observed biomass values at the end of the growing season are also given.

	Region	Potential	Water-limited
Observed biomass values at end of the growing season (kg dry matter ha^{-1})	Northern	16668	15230
	Southern	17494	13422
Average absolute error (kg dry matter ha^{-1})	Northern	1215	1327
	Southern	1156	1410
Normalized average error (%)	Northern	14.6	17.4
	Southern	13.2	21.0

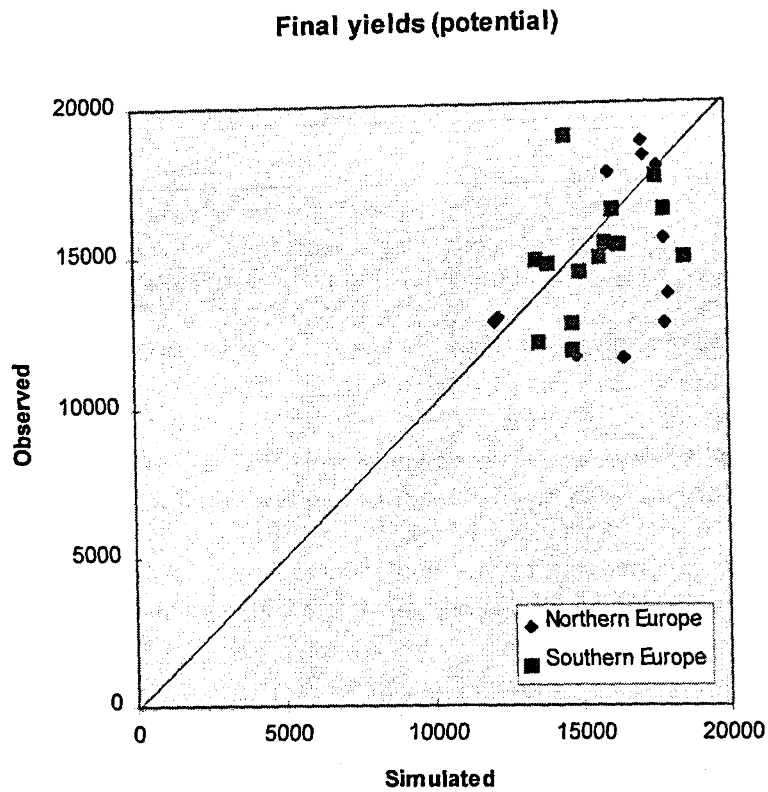

Figure 3.6a. Observed against simulated values of total harvested product at the end of the growing season on the level of potential production. Diamonds indicate the Northern European sites; squares the Southern European sites.

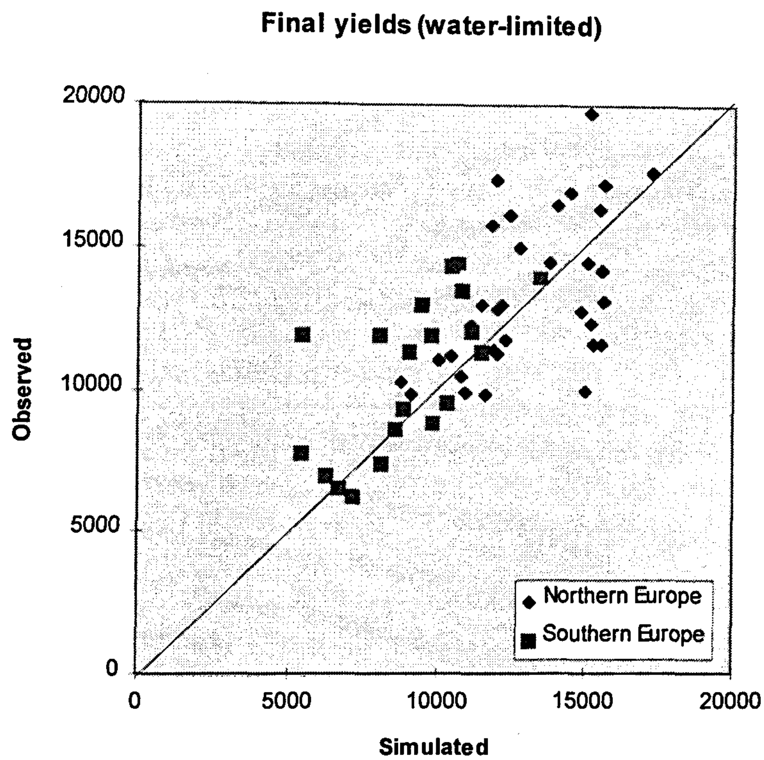

Figure 3.6b. Observed against simulated values of total harvested product at the end of the growing season on the level of water-limited production. Diamonds indicate the Northern European sites; squares the Southern European sites.

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Appendix I: variable name listing

Name	Explanation	Units
A	Factor in calculation of soil water depletion factor	-
B	Factor in calculation of soil water depletion factor	-
CFET	Correction factor for transpiration rate	-
CGNR	Crop group number	-
CINT	Cumulative daily amount of absorbed PAR	MJ.ha-1
CLAI	Remaining leaf area index after cutting	ha leaf ha groun
COCON	Atmospheric CO2 concentration	ppm
CRAIRC	Critical air content in the root zone	(cm3 cm-3)
CTRA	Cumulative transpiration	cm
CWGHT	Criterium for mowing when MOPT equals 1	kg ha-1
CWLVG	Remaining leaf weight after cutting	kg ha-1
DAHA	Number of days after latest cutting	d
DD	Effective depth of drains (drainage base)	cm
DELT	Time interval of integration	d
DEPNR	Crop group number for soil water depletion	-
DLAI	Death rate of leaf area	ha.ha-1.d-1
DLAIS	Rate of sink limited leaf growth	tillers m-2
DLV	Death rate of leaf biomass	kg leaf.ha-1.d-1
DRE	Rate of decrease of short lived carbohydrate pool	kg CH2O.ha-1.d
DSOS	Number of days since start of oxygen shortage	d
DT	Estimated temperature difference between surface height and reference height	degrees C
DTIL	Rate of tiller formation	tillers m-2 d-1
DTILD	Relative death rate of tillers due to self-shading	tiller tiller-1 d-1
DVS	Development stage of the crop	-
E0	Potential evapotranspiration	cm d-1
EKL	Intermediate variable in calculation of evaporation	mm d-1
ELEV	Elevation of site	m
ES0	Potential soil evaporation	cm d-1
ET0	Potential transpiration	cm d-1
ETAE	Dryness driven part of potential evapotranspiration	mm.d-1
ETC	Crop specific correction on potential transpiration rate	cm d-1
ETD	Potential evapotranspiration	mm.d-1
ETMOD	Name of evapotranspiration module used in simulation	-
ETRD	Radiation driven part of potential evapotranspiration	mm.d-1
EVSMX	Maximum evaporation rate from soil surface	cm d-1
EVWMX	Maximum evaporation rate from water surface	cm d-1
FILEI1	Name of input file no. 1	-
FILEI2	Name of input file no. 2	-
FILEI3	Name of input file no. 3	-
FILEIN	File name with which model parameters are read	-
FILEIT	Name of timer file	-
FINT	Fraction interception	-
FLV	Fraction of shoot dry matter allocated to leaves	-