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Grassland simulation with the LPJmL model

Version 3.4.018

E.R. Boons-Prins

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Wettelijke Onderzoekstaken Natuur & Milieu

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Grassland simulation with the LPJmL model

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WOt Working Document **172** presents the findings of a research project commissioned by the Netherlands Environmental Assessment Agency (PBL) and funded by the Dutch Ministry of Agriculture, Nature and Food Quality (LNV). This document contributes to the body of knowledge which will be incorporated in more policy-oriented publications such as the Nature Balance and Environmental Balance reports, and Thematic Assessments.

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Abstract
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One third of the land surface is covered with natural and cultivated grasslands. Most of these grasslands are intensively or extensively exploited by humans to feed animals. With growing wealth, causing an increase of meat consumption, there is a need to better understand the processes that influence the grass production of these ecosystems. The project aims to improve the knowledge basis regarding grassland productivity and the relationship between management of grasslands and productivity. The research will led to modification of the Dynamic global vegetation model with natural and managed land (LPJmL, version 3.4.018, 2010) for the simulation of grassland and grassland management. Crop growth models such as LPJmL can help to clarify and understand grass production processes. A checked and calibrated model gives useful insights in the carrying capacity of grasslands and enables us to estimate the risk for environmental damage with increase of grass and/or meat production.

Key words: crop growth modeling, land use, LINGRA, LPJ

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Preface

Grassland areas cover more than a third of the worlds land surface, and many of them are used for grazing or grass production. However, productivity and management of grassland systems are still poorly understood.

For grasslands, productivity and biodiversity strongly depends on the natural environment (climate and soil fertility) and management like animal density. Therefore, for the biodiversity assessments, management of grasslands and grazing intensities need to be better understood and investigated. For the agricultural assessments, the future demand for grassland is an important determinant. As presented in a recent study on changing meat consumption, the changes in grassland area and their management can potentially have a major impact on their biodiversity but also on the global carbon cycle, and therefore on climate policy.

The aim of this project is to improve the knowledge basis regarding grassland productivity and the relationship between management of grasslands and productivity. The research should lead to a modification of the Dynamic global vegetation model with natural and managed land (LPJmL, version 3.4.018, 2010) for the simulation of grassland and grassland management.

This project has been made possible by the financial support of the Statutory Research Tasks Unit for Nature & the Environment (WOT Natuur & Milieu). I am grateful for the advices and interesting discussions with J. Wolf and P.A. Leffelaar and other colleagues of Plant Production Systems Group and L. Bouwman of the Netherlands Environmental Assessment Agency (PBL). Thanks for the cooperation of other colleagues of PBL and Potsdam Institue for Climate Impact Research (PIK).

Wageningen, July 2010

Eltje Boons-Prins

Contents

1 Summary and conclusions

The aim of this project is to improve the knowledge basis regarding grassland productivity and the relationship between management of grasslands and productivity. The research should lead to a modification of the Dynamic global vegetation model with natural and managed land (LPJmL 3.4.018) for the simulation of grassland and grassland management.

The model LPJmL is based on the Lund-Potsdam-Jena Dynamic Global Vegetation Model. LPJmL means Lund-Potsdam-Jena managed land, which simulates carbon and water cycles of natural vegetation and productivity and carbon yield of the most important crops worldwide. The calculations are based on biophysical and biochemical processes (Bondeau *et al.*, 2007). Within grid cells of 0.5° (approximately 50 x 50 km) the yield of nine plant functional types (PFT) including C_3 and C_4 grass, and eleven crop functional types (CFT) are simulated.

This report describes the investigation of global grassland production by use of the vegetation model LPJmL. After the summary and conclusions in this chapter an introduction is given in Chapter 2. A general overview of grasslands in the world and detailed information of distribution of vegetation due to climate, suitability of soil for plant growth and background information about the physiology of C_3 and C_4 photosynthesis are given in Chapter3. The LPJmL code is described in Chapter 4. First, the environmental input of the model is regarded with emphasis on the photosynthetically active radiation and the absorbed photosynthetically active radiation, which LPJmL uses to calculate the gross carbon production. The research continues with the consideration of the photosynthesis process and gross and net water limited carbon production and respiration losses for C_3 and C_4 grasses. The method used to allocate the produced carbon to leaves and root by a calculated root/shoot ratio is described in detail. The method used to simulate a harvest in the model is described concluding with the consequences of these methods for the calculation of above and belowground carbon production. Flowcharts are presented of important moments in a grass grow run like a harvest when the root/shoot ratio is too high or too low and at the last day of the year. As a final check the C-balance of one year is given. The chapter ends with conclusions about the LPJmL procedures. In Chapter 5, the results of LPJmL are compared with a global dataset of actual grass production on 23 different locations. At the end of the chapter the overall conclusions about this comparison are given. In Chapter 6 a start is made to investigate the management aspects, which could enhance the scope of LPJmL.

Human utilization of natural grasslands can be scaled from extensive to intensive. There is a whole range of measures humans can apply to change grassland production to meet their needs. For this study C_3/C_4 grasses, amount of animals and animal species, legumes, fire and use of fertilizer are chosen (Figure 132).

Conclusions for the LPJmL code for grass production

1) LPJmL calculates the net rate of change of carbon per day and accumulates the carbon during inter harvest periods (parameter `bm_inc`). LPJmL allocates the accumulated net carbon amount to leaf, root and litter only on a harvest moment.
   At a harvest moment, the amount of incremented carbon produced between harvests is first divided between roots and leaves. Than, half of the amount of carbon in the leaves is harvested and the remainder stays in the leaves. Because the amount of carbon in the harvested leaves, is half the amount of aboveground carbon in living leaves, the

aboveground carbon from LPJmL may be calculated as the amount of carbon in the leaves times two. (If a quarter of the amount of carbon of the leaves would have been harvested the aboveground carbon would have been calculated by the amount of carbon in the leaves times four.) Even after this adjustment, it is difficult to compare the total aboveground carbon of biomass in measurements (g C m^{-2} or g dm m^{-2}).

In LPJmL, the senescence of the grass is not calculated during the growing season but, apparently, an amount of carbon in the leaves is sent to litter when the root/shoot ratio is too low (may be the first harvest) (see conclusion 3 on this item) and at the end of the year. This causes a continuing increase of the calculated amount of carbon in the leaves during the growing season whereas the measured amount of carbon in living leaves reduces towards the end of the year (Figure 1 which is the same as Figure 57 from 5.1.1).

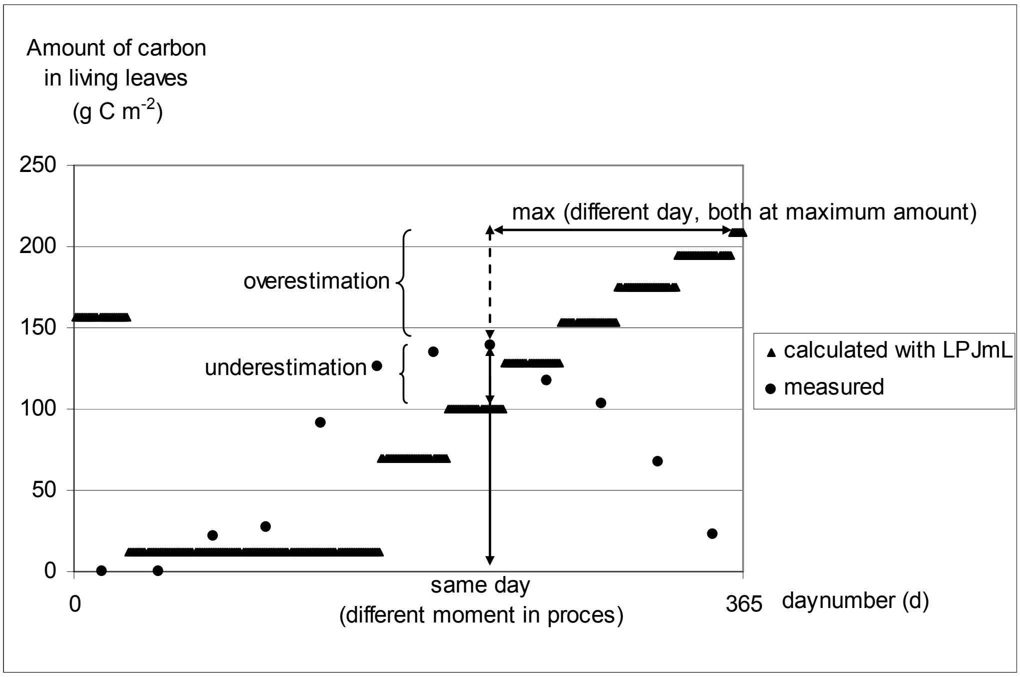


Figure 1 Measured and calculated amount of carbon in living leaves (g C m^{-2})

The comparison between measured and calculated carbon production may take place on the same day (but with different amounts of carbon produced, Figure 1, 'same day') or the maximum production of the calculated and measured data can be compared (on different days) (Figure 1, max).

This prohibits a correct comparison of measured and calculated carbon:

- on the same day, because the calculated value has not reached its maximum on the day the measured value has and this suggests an incorrect underestimation by LPJmL.
- at maximum production, because than the timing is wrong.

Recommendation: total amount of accumulated carbon allocated to the leaves, roots and above- and belowground litter should be provided in the output by LPJmL. This is a matter of output regulation.

Recommendation: allocations of carbon to roots and leaves should take place on a daily basis to solve this problem.

(The first options would be a matter of output regulation; the second option is more fundamental and demands to reconsider a part of the model structure.)

2) In the model, the leaf area index (LAI) is calculated by multiplying the amount of carbon in the leaf (constant between harvests) by the SLA (which is a constant) and the phenology (which increases from 0 to 1 after a harvest). During the period after the harvest, the LAI increases until the value of the phenology is 1, than the LAI stays on that level until the next harvest because the amount of carbon in the leaves does not change between harvests.

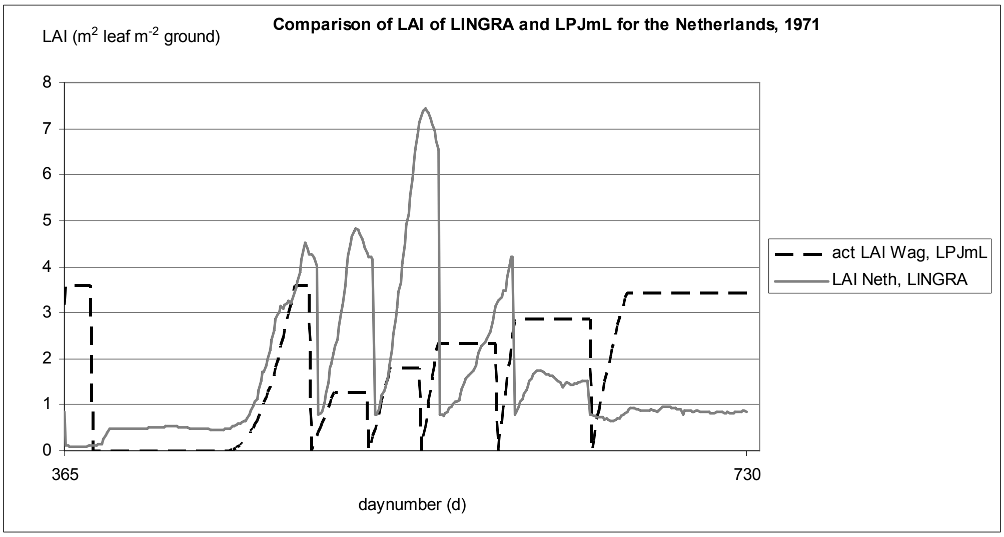


Figure 2 Comparison of LAI between LPJmL and LINGRA.

For example, the LAI of LPJmL starts with 3.8 than decreases to 1.3 and increases towards 3.5 at the end of the year (Figure 2).
For LINGRA, the maximum values of the LAI between the harvests follow a curved line. The first maximum LAI, calculated by LINGRA, is 4.3, the second maximum LAI is 4.8, next 7.4 and than a decrease to 4.1 and 1.8 (Figure 2).
The constant value of the LAI, calculated by LPJmL, between harvests is no problem, but there is quite a difference in dynamics of the constant value of LAI between the harvests during the year between LINGRA (and nature) and LPJmL. High levels of LAI at the end of the years suggest a high interception of light at the end of the year, which does not happen in reality because of a decrease in amount of (carbon in the) leaves.

Recommendation: when the previous problem (1) is solved according to the second recommendation, the LAI will follow a more natural course as well.

3) As long as only the amount of aboveground biomass is asked for, LPJmL calculates the amount of grass quite well for half of the experimental sites (Figure 3 which is the same as Figure 59 in 5.1.1). However, if more detailed information is needed, like the decrease of grass production at the end of the year, this is not simulated according to the measured data. In LPJmL, the senescence of living tissue is not based on physiological processes such as ageing of leaves or an exponential decrease with a relative mortality rate. The senescence of leaves is mimicked by sending carbon of the leaves to leaf litter at two possible occasions. One occasion is when the root/shoot ratio is too low and the amount of carbon in the leaves needs to be reduced (this happens sometimes at the first harvest). The other occasion is at the end of the year (day 365) when half of the leaf biomass is allocated to leaf litter and half to harvest.

Recommendation: If the allocation of biomass to roots and leaves is changed to a daily event, it is possible to take the senescence into account in the process.

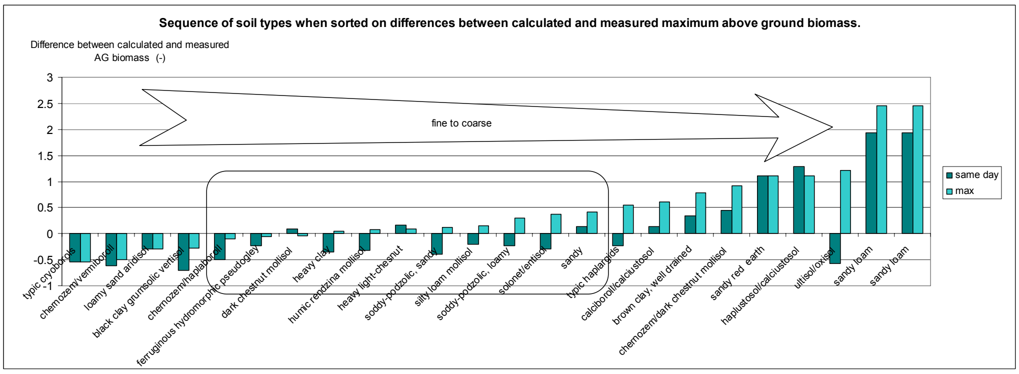


Figure 3 Difference between calculated and measured maximum aboveground biomass on the same day (same day) and measured maximum aboveground biomass in comparison with the maximum aboveground biomass LPJmL calculates for that year (max) per soil type sorted for 'max'.

4) In 14 of the 23 investigated experiments, the graph of the aboveground biomass has the same shape as the graph of the measured aboveground biomass at the beginning of the growing season. This means that the amount of calculated aboveground biomass increases with the same rate as the measured aboveground biomass does when the growing season starts. But in 9 cases the calculated biomass seems to lag behind in time compared to the measured data, sometimes due to a delay in harvest moment, sometimes due to delay in growth.
   When only the total harvest at the end of the year is of interest (and not the biomass increment from day to day) this is no problem.
   However, with grazing scenarios the grazing capacity will be underestimated when compared with the harvest (available fodder).

   Recommendation: to be able to investigate grazing scenarios with LPJmL, the reasons for the seemingly retarded aboveground biomass development (as compared to data) and the daily available amount of biomass should be known.

5) When harvest conditions are not met, the current threshold amounts to 100 g C m^{-2} together with a value one of the phenology, there is no harvest. This leads to an underestimation of the potential carrying capacity of the land for low productive areas like Mongolia (see comparison between calculated total living biomass and calculated available biomass).

   Recommendation: living aboveground biomass calculations should be provided in the output by LPJmL together with harvest values.
   Recommendation: investigation on the effect of lowering the threshold of 100 g C m^{-2} on living aboveground production and harvest.

6) When the global harvest of LPJmL is compared with the global demand for grass of IMAGE, some places like Mongolia seem to have an excess in grass. When the grass consumption (IMAGE) is divided by the grass production (calculated by LPJmL) this ratio is 0.1 for Mongolia (overgrazing has a ratio value > 1). This is strange, because there tend to be overgrazing in this area. Either LPJmL overestimates the grass production or the

grass demand (amount of grass eating animals) from IMAGE is too low. The density of grazing animals in IMAGE is calculated as the total number of animals, divided by the land area of the whole of the country. This approach causes a low animal density and assumes that bare soil is also grazed.

Recommendation: One way to solve this problem is to allocate grazing animals to grass producing grids only. This needs to be fixed between the two models LPJmL and IMAGE. To get an idea of the potential production and carrying capacity it is valuable to have the aboveground biomass and the harvest in the output.

7) In LPJmL, the absorbed photosynthetically active radiation (APAR) is a parameter from the photosynthesis function, used to calculate the carbon production. APAR is calculated from the photosynthetically active radiation (PAR, J $m^{-2}d^{-1}$) multiplied by the fraction of incoming PAR intercepted by green vegetation (FPAR, (–) and $alpha_a$ (–). This $alpha_a$ is an empirical parameter that accounts for reductions in PAR utilization efficiencies in natural ecosystems and is assigned a value of 0.5 based on quantum efficiencies from field and laboratory measurements. This reduction factor is quite substantial (in comparison to 1) and when the total calculated biomass matches the actual measured biomass as is the case in Thailand, there is no room for management factors like fertilization and pests and diseases. For managed grassland, $alpha_a$ could be made a function of these management factors.

   Recommendation: the effect of $alpha_a$ on the grass production calculated by LPJmL needs further investigation; what is the exact meaning of $alpha_a$ and is it necessary. In particular, it should be clarified whether management factors are taken into account elsewhere in the model, or that $alpha_a$ could be used for that purpose.

8) For Dutch practice, LPJmL does not reach the very high and validated production levels of LINGRA.

   Recommendation: maybe this problem is solved when the $alpha_a$ parameter is set to one. Otherwise, the assumptions on LAI and the water supply and demand should be checked.

   The following conclusions are about the choice for C_3 or C_4 grasses in LPJmL. The choice for C_3 or C_4 grasses by the LPJmL model is based on a temperature threshold. When the average minimum temperature over 20 years is below 15.5°C, LPJmL chooses C_3 for a grid and above this threshold LPJmL calculates the carbon production for a C_4 grass.

9) When LPJmL is run for the SINGLECROP and GRASSLAND option, for a location where C_3 or C_4 grass species grow, the calculated accumulated biomass is given correctly in the output. However, when both plant species occur in the same grid the C_4 output overwrites the C_3 output.

   Recommendation: when both C_3 and C_4 grasses are present in a grid both carbon productions should be available in the output. This is a matter of output regulation.

10) The model LPJmL wrongly chooses C_3 instead of C_4 on at least two locations; India and Spain. These are locations with great differences between cold and warm periods (seasons, day/night). This leads to an average minimum temperature over 20 years below the 15.5°C threshold and LPJmL chooses C_3 instead of C_4, which is the local dominant grass species.

C_4 plants are rare at altitudes and latitudes where growing season temperatures are less than an average of approximately 16°C and minimum midsummer temperatures average less than 8°C to 12°C (Long, 1983). Thus, not the average minimum over 20 years should be above 15.5°C, but the average temperature should be above 16°C and the minimum midsummer temperature should be above 8°C to 12°C. Moreover, for locations with monsoon-climates, the distribution of the precipitation is important too (Sage, 1999). Another example of the role of water is an experiment in Mongolia where a shift to C_3 occurs instead of C_4 when the circumstances are drier. However, this may be a local reaction and too detailed for a global simulation model.

Recommendation: the deciding parameter for C_3 and C_4 grasses (average minimum temperature over 20 years) and the necessity to implement dependence of C_3 or C_4 choice on precipitation distribution needs further investigation.

11) In the model, the phenology is the same for C_3 and C_4 grasses, although the phenology of these grass species is different see Figure 4, same as Figure 133 from section 6.3 (Sage, 1999).

Recommendation: investigation of phenology for C_3 and C_4 grasses.

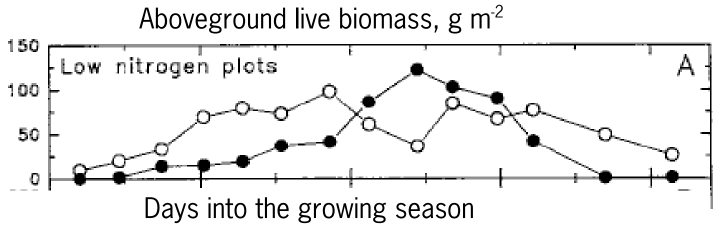


Figure 4 Seasonal patterns of aboveground live biomass for C_3 (open circles) and C_4 (closed circles) vegetation in an east-central Minnesota sand prairie. Low nitrogen plots were unfertilized. Day 0 of the growing season is April 15. (D. Wedin, 1985, unpublished data. See Tilman, 1988, for details of the study site and methods) (Sage et al., 1999).

12) In LPJmL, the allocation of accumulated biomass to roots and leaves is determined by a parameter called `lmtorm`. This parameter is calculated as the parameter lmro_ratio (0.75 (-) times the available water in the previous period (wscall_mean/365), hence it does not depend on grass species. However, there is a big difference between C_3 and C_4 grasses in allocation ratio. In Australia an endemic C_3 grass has a shoot/root ratio of 0.9 ((110 g m^{-2})/(122 g m^{-2})) and C_4 (buffel grass) a shoot/root ratio of 2.6 ((400 g m^{-2})/154 g m^{-2})).

Recommendation: both the 0.75 and the effect of the water balance on the allocation parameter and LPJmL calculated grass production needs further investigation.

13) High overestimations of aboveground living biomass (Figure 5 same figure as Figure 58 from 5.1.1) may be caused by an overestimation of water availability on course sandy soils.

Recommendation: on course soils, the water balance and water holding capacity needs further investigation with respect to calculated grass production by LPJmL.

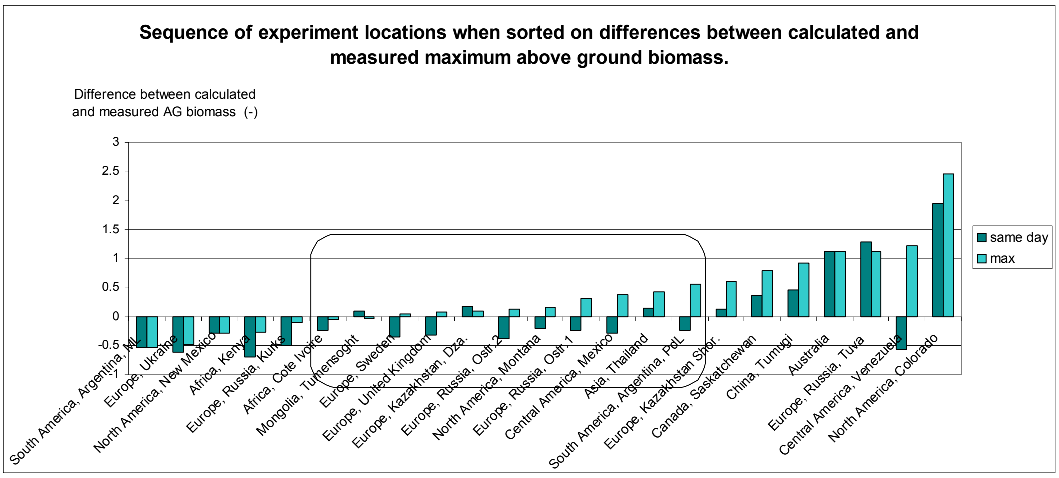


Figure 5 Difference between calculated and measured maximum aboveground biomass on the same day (same day) and measured maximum aboveground biomass in comparison with the maximum aboveground biomass as calculated by LPJmL for that year (max) per region, data sorted for 'max'.

14) In LPJmL there is one fixed value for SLA = 0.04 m^2 leaf g^{-1} C leaf. This may be too rigid. SLA of perennial grasses has values between 0.03 and 0.06 m^2 g^{-1} C leaf, but annuals have higher levels between 0.06 – 0.08 m^2 g^{-1} C leaf.

    Recommendation: the effect of different SLA values on calculated biomass production by LPJmL should be investigated (sensitivity analysis).

15) During a global run, the check of the carbon balance may cause an error message.

    Recommendation: investigate the cause of the problem; a suggestion is to perform a carbon balance check at the end of each year.

Conclusions about management

1) In IMAGE, the amount of grass needed for animal consumption is calculated. In LPJmL, the amount of harvested grass is calculated without taking into account the amount of grazing and mowing losses, which will reduce the harvest and increase the amount of litter.

   Recommendation: Estimations of grazing losses depending on grass consumption (IMAGE)/grass production are presented in Figure 6, which is the same as Figure 140 in subsection 6.7.2

2) The model LPJmL decides internally where C_3 and C_4 grasses are grown. PBL would like to run scenario's with the option that when a farmer decides to grow a C_4 on a location where a C_3 grass usually grows or vice versa (less obvious).

   Recommendation: It should than be possible that the IMAGE model controls this choice, rather than LPJmL.

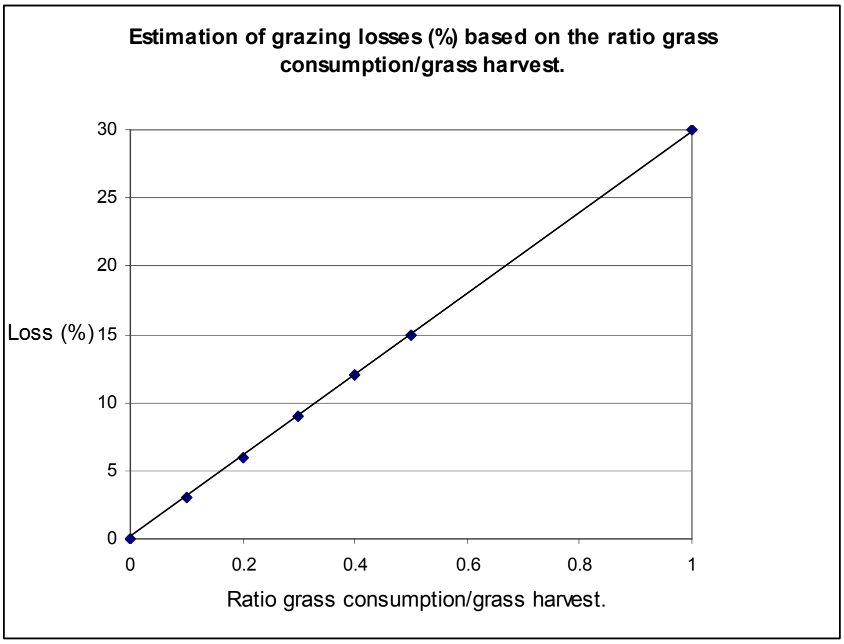


Figure 6 Estimation of grazing losses bases on the ratio grass consumption/grass harvest.

3) PBL would like to make scenario's to investigate the effect of fire (if the nutrients are added to LPJmL) hence this decision should be controlled by IMAGE (with the boundaries for litter and water content set in LPJmL as they are now).

   Recommendation: It should than be possible that the IMAGE model controls this choice, rather than LPJmL

4) IMAGE reports the amount of nutrients used per grid. These numbers could be explored by LPJmL if the model would be further developed to include nutrient dependent grass growth. In the developed regions like West Europe, the impact of adding nutrient depending growth may not be very large, but in the developing areas, this may be substantial. There are examples where low P and K inputs result in substantial yield improvements (Buresh and Giller, 1998 and Buresh *et al.*, 1997).

   Recommendation: It would be an advantage if the presence of legumes could be accounted for in LPJmL, as legumes can e.g. contribute to up to 215 kg N ha^{-1} under Dutch conditions.

5) The quantity of grass production is important, but the quality is the next challenge to accomplish. Quality has several aspects. Some important ones are mentioned here. The crude protein content is closely correlated to the amount of nitrogen. This plays a role with items like animal production (growth), legumes and fire. Another aspect is digestibility correlated to age of plant material and plant species (palatable grasses in comparison to thistles). There is no simulation of quality in LPJmL yet. It is to be expected that the effect of nutrients on yield and quality is higher in the tropics, with poor and phosphorous fixing soils with low organic matter, than in Western Europe.

2 Introduction

Grassland areas cover more than a third of the worlds land surface, and many of them are used for grazing or grass production. However, productivity and management of grassland systems are still poorly understood.

For grasslands, productivity and biodiversity strongly depends on the natural environment (climate and soil fertility) and management like animal density. Therefore, for the biodiversity assessments, management of grasslands and grazing intensities need to be better understood and investigated.

For the agricultural assessments, the future demand for grassland is an important determinant. As presented in a recent study on changing meat consumption, the changes in grassland area and their management can potentially have a major impact on their biodiversity but also on the global carbon cycle, and therefore on climate policy.

2.1 Aim of the project

More than one third of the land area is covered by grassland. The area covered by grassland is changing due to climate change and changing human activity. Humans use grasslands extensively or intensively, for direct grazing by animals or harvesting. Because of the increase of wealth meat consumption increases and the demand for more or better fodder rises. In this context, it is important to know what the carrying capacity of a country or region is. Is it possible to increase livestock density without the risk of overgrazing? With the use of a dynamic global vegetation model like LPJmL the water limited grass production may be estimated and the results compared with the total grass demand of livestock.

In Figure 7 an impression of the distribution of grasslands around the world is given.

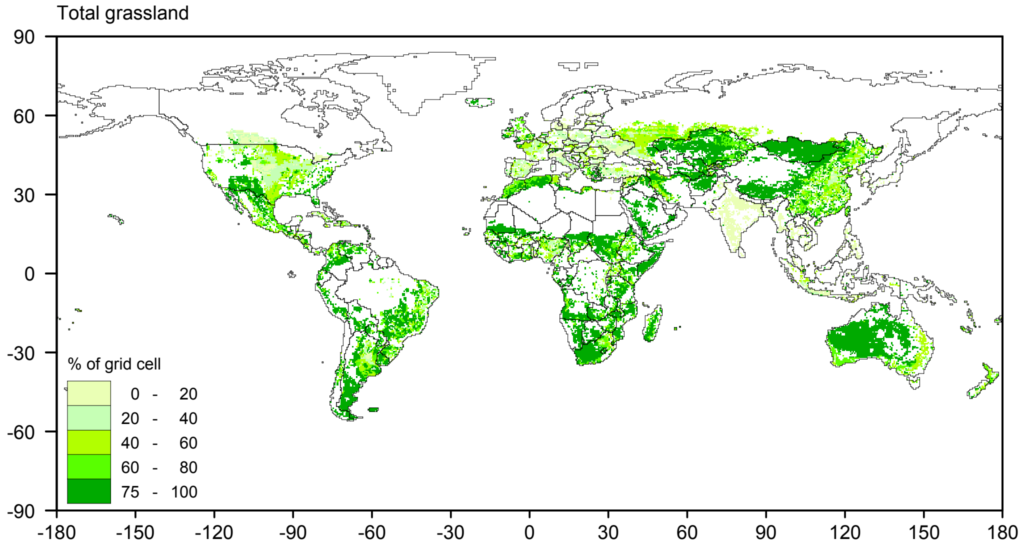


Figure 7 Distribution of grassland (IMAGE, 2000) (Pers. comm. L. Bouwman, PBL, 2010).

The aim of this project is to describe, check and, if necessary, improve the existing routines for calculation of grass productions of the Dynamic global vegetation model with natural and managed land (LPJmL version 3.4.018, 2010).

2.2 Report layout

This report describes the investigation of global grassland production by use of the vegetation model LPJmL. After the summary and conclusions in Chapter 1 an introduction is given in this chapter. A general overview of grasslands in the world and detailed information of distribution of vegetation due to climate, suitability of soil for plant growth and background information about the physiology of C_3 and C_4 photosynthesis are given in Chapter 3. The LPJmL code is described in Chapter 4. First, the environmental input of the model is regarded with emphasis on the photosynthetically active radiation and the absorbed photosynthetically active radiation, which LPJmL uses to calculate the gross carbon production. The research continues with the consideration of the photosynthesis process and gross and net water limited carbon production and respiration losses for C_3 and C_4 grasses. The method used to allocate the produced carbon to leaves and root by a calculated root/shoot ratio is described in detail. The method used to simulate a harvest in the model is described concluding with the consequences of these methods for the calculation of above and belowground carbon production. Flowcharts are presented of important moments in a grass grow run like a harvest when the root/shoot ratio is too high or too low and at the last day of the year. As a final check the C-balance of one year is given. The chapter ends with conclusions about the LPJmL procedures. In Chapter 5, the results of LPJmL are compared with a global dataset of actual grass production on 23 different locations. At the end of the chapter the overall conclusions about this comparison are given. In Chapter 6 a start is made to investigate the management aspects, which could enhance the scope of LPJmL.

3 Grasslands of the world

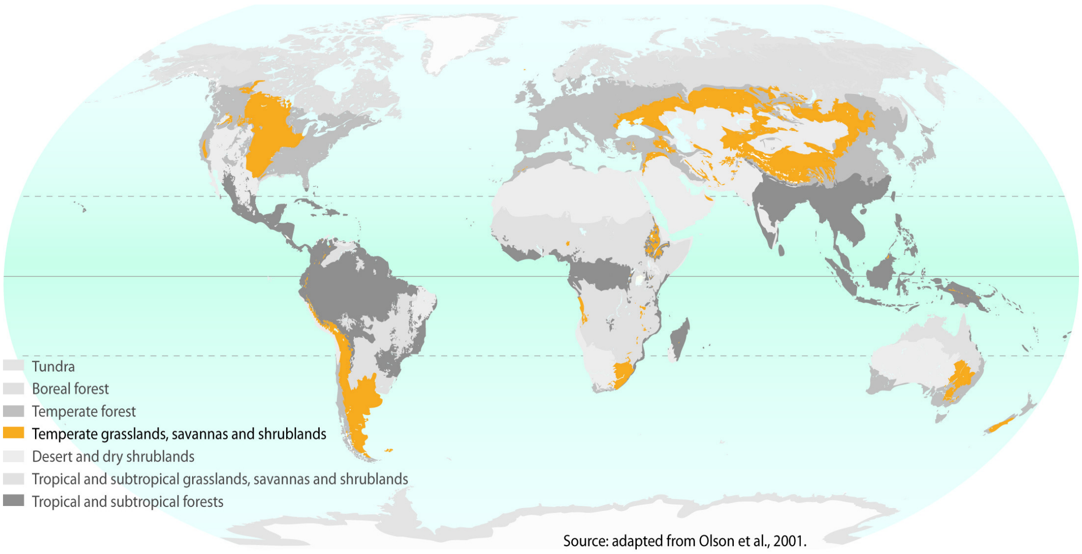
Grasslands occur naturally on all continents except Antarctica. They are found in most terrestrial climates. Grasslands are characterized as lands dominated by grasses (Poaceae) and other herbaceous (non-woody) plants (forbs) like sedge (Cyperaceae) and rush (Juncaceae) families. In temperate latitudes, such as northwest Europe, grasslands are dominated by perennial species, where as in warmer climates annual species form a greater component of the vegetation (http://en.wikipedia.org/wiki/Grassland#Tropical_and_subtropical_grasslands).

3.1 Distribution of grasslands

The grasslands around the world may be divided into temperate and (sub) tropical grasslands.

Temperate grasslands are mid-latitude grasslands, including the Prairie of North America, the Pampas of Argentina, calcareous down land, and the steppes of Europe (Figure 8). They are classified with temperate savannas and shrubland as the temperate grasslands, savannas and shrubland biome.

Temperate grasslands are characterized as having grasses as the dominant (only) vegetation. Trees and large shrubs are absent. Temperatures vary more from summer to winter, and the amount of rainfall is less in temperate grasslands than in savannas. The major examples of temperate grasslands are the veldts of South Africa, the puszta of Hungary, the pampas of Argentina and Uruguay, the steppes of the former Soviet Union, and the plains and prairies of central North America.

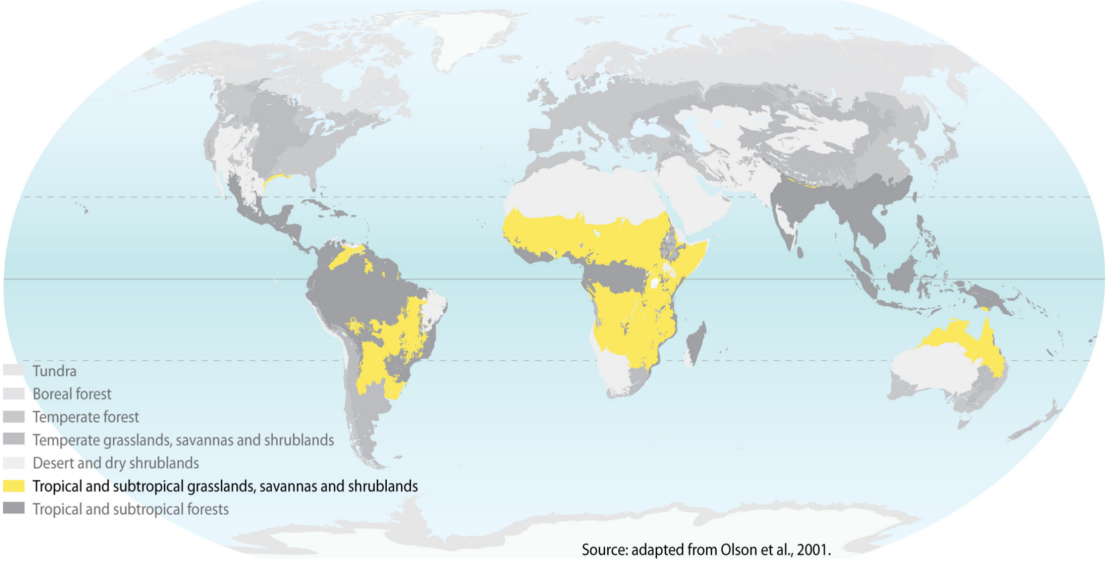


Source: adapted from Olson et al., 2001.

Figure 8 Distribution of temperate grasslands around the world (http://maps.grida.no/go/graphic/temperate-grasslands, *Riccardo Pravettoni, UNEP/GRID-Arendal).*

Tropical and subtropical grasslands are classified with tropical and subtropical savannas and shrubland as the tropical and subtropical grasslands, savannas, and shrubland biome.

Notable tropical and subtropical grasslands include the Llanos grasslands of northern South America (Figure 9). A savanna is grassland with scattered individual trees. Savannas of different types cover almost half the surface of Africa (about five million square miles, generally central Africa) and large areas of Australia, South America, and India (http://www.ucmp.berkeley.edu/exhibits/biomes/grasslands.php).)



Source: adapted from Olson et al., 2001.

Figure 9 Distribution of tropical and subtropical grasslands around the world. (http://maps.grida.no/go/graphic/savannas-and-tropical-grasslands, Riccardo Pravettoni, UNEP/GRID-Arendal)

3.1.1 Climate

The distribution of grasslands around the world is caused by the global climatic zones with temperature and annual precipitation as the main environmental characteristics (Holdridge, 1947). Henderson-Sellers (1990) adjusted the work of Holdridge for natural grasslands and created two live zones with grasses one) tropical grass and shrub and two) other grass and shrub. The temperature and precipitation boundaries of these life zones are given in Table 1.

Table 1 Two life zones suitable for natural grasslands related to temperature and precipitation boundaries according (Henderson-Sellers, 1990).

	Life zone	**BATS vegetation type**
$T \geq 21$ & $250 \leq P < 500$	tropical grass and shrub	crop, short grass, tall grass, irrigated crop, evergreen shrub, deciduous shrub
$3 \leq T < 10$ & $125 \leq P < 250$ or $6 \leq T < 21$ & $250 \leq P < 500$	other grass and shrub	bog or marsh

T = mean annual biotemperature (definition see text) derived from seasonal means (°C),
P = total annual precipitation (mm).

Biotemperature is defined as the sum of the temperatures over a year with each temperature value (daily, weekly, monthly or seasonal) set to 0˚C if it is less than or equal to 0˚C; this sum is then divided by the total number of values (i.e., 12 for monthly temperatures) (Holdridge, 1947).

In a temperate climate, the rainfall is moderate and precipitation usually occurs in the late spring and early summer. The annual average is about 51 to 89 cm (http://en.wikipedia.org/wiki/Grassland#Climate). The amount of annual rainfall influences the height of grassland vegetation, with taller grasses in wetter regions. Seasonal drought and occasional fires are very important to biodiversity. However, their effects are not as dramatic in temperate grasslands as they are in savannas.
Temperate grasslands have hot summers and cold winters hence the temperature range is very large over the course of the year. Summer temperatures can be well over 38° C, while winter temperatures can be as low as – 40° C.

The (sub) tropical climate creates the savannas. They are always found in warm or hot climates where the annual rainfall is from about 51 to 127 cm per year (http://www.ucmp.berkeley.edu/exhibits/biomes/grasslands.php). It is crucial that the rainfall is concentrated in six or eight months of the year, followed by a long period of drought when fires can occur. If the rain were distributed more uniformly throughout the year, many such areas would become tropical forest (http://www.ucmp.berkeley.edu/exhibits/biomes/grasslands.php).

Besides the climate, the suitability of soils for plant growth is a crucial environmental characteristic as well. This is the topic of the next section.

3.1.2 Soil

In 3.1.1, the effect of climate zones on appearance of vegetation types is described. However, there is a profound influence of soil characteristics on suitability of soils to support plant life. A description of a land evaluation method exists with soil parameter values by FAO soil unit (FAO-Unesco, 1974) which are taken from the ISRIC-IFPRI study (Batjes, 2002a; Batjes, 2002b). Information on soil drainage classes is taken from Batjes (1997). Soil parameter estimates are available for both the topsoil (0-30 cm, TM) and subsoil (30-100 cm, BM, or shallower where applicable). In case of shallow soils (<30 cm by definition; e.g., Lithosols), topsoil values are assigned to the “subsoil”.

This method uses soil characteristics like soil pH (in H_2O), organic carbon content (ORGC), soil Cat ion Exchange Capacity (CEC). Other characteristics are:

- ease of cultivation,
- moisture holding capacity to 1 m depth (pF2.0 to pF4.2; corrected for gravel content),
- depth to physical limitations (DEPT), excess of salts (based on most limiting rating/value for EC_e or ESP),
- EC_e, electrical conductivity of the saturation extract,
- ESP, exchange sodium percentage,
- soil toxicity (aluminium saturation ALSAT),
- soil drainage (total available water capacity, TAWC and gravel percentage (GRAVEL)) (Table 2).

The land evaluation procedure is developed for an ‘average’ annual crop, comparable to maize, using criteria for rating land qualities derived from various sources (Anon, 1984; FAO, 1983; Landon, 1991; Sys *et al.*, 1993), assuming ‘moderate to high input levels’ are feasible. The principles adopted follow the Framework for land Evaluation (FAO, 1976). These characteristics are based on information of N.H. Batjes, ISRIC - World Soil Information (2004) and L. Bouwman (PBL), 2009.

The characteristics of Table 2 are used in a weighing/rating procedure after Batjes & Bouwman (1989). In case of soil chemical properties, each soil is given a rating. Individual ratings or reduction factors by soil parameters are as follows.

Table 2 Class limits used in rating procedure

	Class					
attribute	1	2	3	4	5	
PHH20_TM	5.5	6.5	7.3	8	8.4	pH (see c)
PHH20_BM	5.5	6.5	7.3	8	8.4	pH
ORGC_TM	0.3	0.6	1	2	4	% OC
ORGC_BM	0.3	0.6	1	2	4	% OC
CECsoil_TM CECs_T	5	10	20	30	40	cmolc kg^{-1}
CECsoil_BM CECs_B	5	10	20	30	40	cmolc kg^{-1}
BSAT_TM	10	30	50	70	90	% of CEC
BSAT_BM	10	30	50	70	90	% of CEC
ALSAT_TM	15	30	45	60	75	% of ECEC
ALSAT_BM	15	30	45	60	75	% of ECEC
ESP_TM	10	15	20	25	30	% of CEC
ESP_BM	10	15	20	25	30	% of CEC
ECE_TM	2	4	8	16	32	dS m^{-1}
ECE_BM	2	4	8	16	32	dS m^{-1}
DEPT	25	50	100	150	200	cm
DRAINY	2	3	4	5	6	see b)
TEXT_T	1	2	3	4	5	see a)
TEXT_B	1	2	3	4	5	see a)
GRAVEL_TM	10	20	30	40	50	%
GRAVEL_BM	10	20	30	40	50	%
TAWC2_M	40	80	120	160	200	mm (from –10 to –1500 k Pa)

a) Soil texture: 1 course, 2 medium, 3 fine, 4 very fine (>60% clay), 5 organic soils

b) Soil drainage: 1 very poorly, 2 poorly, 3 imperfectly, 4 moderate well, 5 well, 6 somewhat excessively, 7 excessively drained.

c) For pH an extra class limit is considered in the rating procedure (pH<4.5).

d) Possible limitations of slope and length of growing period are not considered in the current rating scheme, and should be derived from auxiliary sources.

val1 =1.0 no to slight limitations
val2 = 0.8 moderate limitations
val3 = 0.6 severe limitation
val4 = 0.2 very strong limitations

Overall rating = (2*rating_for_topsoil+1*rating_for_subsoil)/3

In case of aluminum toxicity, however, the weighing factors are set at 1 and 2 respectively. For saline/sodic soils, the weighing factors are both set at 1. A correction factor is used for impeded drainage as well as for the occurrence of impervious layers:

- at shallow depth (e.g. for Planosols), i.e. $val_i = val_i - 0.2$, when rating effective soil depth for' physically deep' soils. This is flagged as 'd';
- In case of Thionic Fluvisols (Jt), the rating for toxicity has been set at 'strongly limiting';
- In case of plinthic soil units (Ap, Lp and Fp), and of Podzols with a thin iron pan (Pp), a reduction factor has been applied to the rating for effective depth (flagged as 'p'). Similarly, such a rating has been applied for all gelic soil units (flagged as 'x') and gleyic units and subunits (flagged as 'g').

The final land suitability rating by soil unit is determined according to:

Final rating = (most limiting rating)*(SUM of other 8 ratings)/8

Inherently, translation of the ratings into an overall suitability class is arbitrary. Table 3 has been selected as being most appropriate based on several test runs and 'sensitivity' analyses.

Table 3 Scheme for rating overall land suitability for given land utilization type.

Suitability rating	Final rating	Number of strong limitations
S1 (highly suitable)	=>0.60	<1
S2 (moderately suitable)	=>0.50–0.60	<=2
S3 (marginally suitable)	=>0.16–0.50	=>2
N (not suitable)	<0.16	>2

Together with the climatic characteristics, these soil characteristics may explain the distribution of grassland around the world.

3.1.3 Soil characteristics of grasslands

In semiarid regions, calcification is the dominant soil–forming process. Mild leaching, high organic content, and concentration of calcium carbonate in the B-horizon typify the dark brown mollisols developed under the temperate grasslands. When this process works on loess that itself is rich in calcium, the world's most fertile soils are created, the chernozems (A Russian term meaning black soil). Loess and hence chernozem underlie the eastern prairies of the US, the pampas of South America, and the steppes of Ukraine and Russia (http://www.runet.edu/~swoodwar/ CLASSES/GEOG235/biomes/tempgrass/tempgras.html).

Although climate and soil characteristics determine the suitability of a site for grass growth, there is an interaction between grass and soil as well. The soil is nutrient-rich from the growth and decay of deep, many-branched grass roots. The rotted roots hold the soil together and provide a food source for living plants. Hence, the soil of the temperate grasslands is deep and dark, with fertile upper layers.

The soil of the savanna is porous, with rapid drainage of water. It has only a thin layer of humus (the organic portion of the soil created by partial decomposition of plant or animal matter), which provides vegetation with nutrients (http://www.ucmp.berkeley.edu/exhibits/biomes/grasslands.php).

3.1.4 C_3/C_4

In LPJmL, there are two plant functional types for grasses: C_3 and C_4 grasses. The difference between these two types originates from different modes of photosynthesis. There are three modes of photosynthesis predominate in terrestrial plants: the C_3 mode, which is employed by higher plant species; the Crassulacean acid metabolism (CAM) mode, employed by 20.000 or more succulents and epiphytes; and the C_4 mode, employed by approximately 8000 of the estimated 250.000 higher plant species. Although far fewer species use the C_4 pathway, their ecological and economic significance is substantial. C_4 plants dominate all tropical and subtropical grasslands, most temperate grasslands, and most disturbed landscapes in warmer regions of the world (Sage & Monson, 1999).

Photosynthesis occurs when ribulose-1,5-biphosphate (RuBP) is carboxylated by Rubisco and the products (two phosphoglyceric acid molecules; PGA) are processed into carbohydrates and used to regenerate RuBP in reaction sequences requiring ATP and NADPH. Photorespiration begins with the oxygenation of RuBP to form one phosophoglycolate (PG) and PGA, in a side reaction catalyzed by Rubisco.

Processing the phosphoglycolate to PGA and eventually RuBP requires ATP and reducing power (indicated by NADPH) (Figure 10) (Sage, 1999).

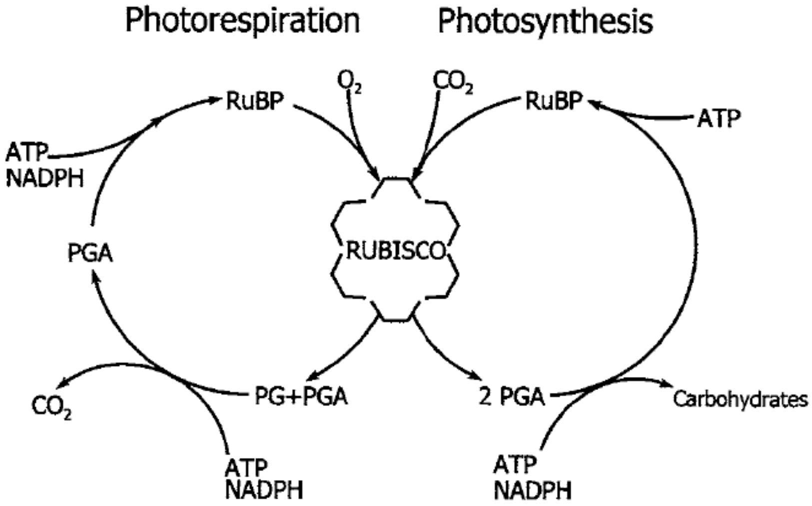


Figure 10 Schematic of the photo respiratory cycle and photosynthesis (Sage, 1999).

The photorespiration (oxygenation) is considered a wasteful side reaction of Rubisco because it uses active sites that otherwise would be used for carboxylation, it consumes RuBP, and the recovery of carbon in phosphoglycolate consumes ATP and reducing equivalents while releasing previously fixed CO_2 (Sharkey, 1985). Oxygenation may be inevitable, given similarities in the reaction sequence for oxygenation and carboxylation of RuBP (Andrews & Lorimer, 1987; Sage, 1999). The relation between photosynthesis and photorespiration can be summarized in the following equation:

$$\frac{photorespiration}{photosynthesis} = \frac{0.5v_0}{v_c} = 0.5(\frac{1}{S} * \frac{O}{C})$$

This equation describes the relationship between Rubisco kinetic parameters and the ratio of photo respiratory CO_2 release to photosynthetic CO_2 fixation (Andrews & Lorimer, 1987; Sharkey, 1988). The term v_0 is the rate of RuBP oxygenation, v_c is the rate of RuBP carboxylation, S is the specificity of Rubisco for CO_2 relative to O_2, C is the CO_2 concentration in the chloroplast stroma, and O is the O_2 concentration in the stroma. According to above-mentioned equation, photorespiration can be reduced by changing Rubisco properties by increasing S, increasing C or reducing O. The most effective means for overcoming photorespiration in terrestrial settings is to raise the CO_2 concentration on an intercellular level, which happens with the C_4 mechanism (Sage, 1999). This elevated concentration has two effects.

First, it causes competitive inhibition of the oxygenase reaction of Rubisco, eliminating most of the photosynthetic carbon oxidation pathway activity and associated energy expenditure that underlies photorespiration.

Second, it allows Rubisco to approach its maximum rate of catalysis despite its low affinity for CO_2 (Long, 1999). Photorespiration is estimated to decrease net carbon gain in C_3 species by 20% to 50% (Zelitch, 1973; Bainbridge *et al.*, 1995). C_4 species avoid most of this loss by concentrating CO_2 at the site of Rubisco in the bundle sheath (Hatch, 1987; Long, 1999).

Compared to ecologically similar C_3 species, C_4 plants generally exhibit higher photosynthesis rates at low CO_2 and elevated temperature and have higher efficiencies of light, water and nitrogen use in warm to hot environments (Sage, 1999; Long, 1999; Knapp & Medina, 1999). These improvements in photosynthesis performance appear to have favored the C_4 grasses in low latitudes, salinized soils and temperate regions with hot summers and some growth season precipitation such that C_4 species often dominate these landscapes (Sage *et al.*, 1999).

These features give directions for the global distribution of C_4 photosynthesis. C_4 plants have two primary requirements for success – warm growing seasons and access to moderate to high light intensity. All other factors such as aridity are secondary in that they influence patterns of C_4 distribution and dominance, but are inconsequential in the absence of both moderate light and warm growth conditions (Sage *et al.,* 1999).

C_4 plants are rare at altitudes and latitudes where growth season temperature are less than an average of approximately 16°C and minimum midsummer temperatures average less than 8°C to 12°C (Long, 1983). Winter temperature is not an obvious factor because C_4 species dominate many temperate locations where severe winter freezing occurs and if dormant, survive freezing as well as their C_3 associates (Long, 1983; Schwarz & Reaney, 1989).

In addition to indices of growing season temperature, a second important temperature aspect is the length of the warm growing season relative to the cool growing season (Doliner & Joliffe, 1979). Besides the temperature the distributions and time of precipitation is important too (Sage *et al.*, 1999).

Walter diagrams show the relation between temperature and precipitation. When the precipitation curve is above the temperature curve, moisture excess occurs, indicative of a wet season. When the temperature curve is above the precipitation curve, a moisture deficit occurs, indicative of a dry season. In Figure 11, Walter diagrams for four different regions are given.

Where the warm season is wet, but the cool season dry, open landscape will be C_4 dominated, as is observed in the monsoon-climates of India and Africa (Figure 11A).

Where the warm season is dry, but the cool season mild and wet (as occurs in the Mediterranean climates of southern Europe, California, western Australia, South Africa and Chile), open landscapes will have few C_4 species, except as weeds in irrigated fields (Figure 11B) (Beetle, 1947; Collins & Jones, 1985; Baker, 1989). Where C_3 and C_4 grasses co-occur, the C_3 element will break dormancy earlier in spring than the C_4 element. In the northern Plains grasslands of North America, the C_3 grasses become active in March to mid-April, while the C_4 species appear in late April to May (Dickinson & Dodd, 1976; Baskin & Baskin, 1977; Ode *et al.*, 1980; Monson *et al.*, 1983). Throughout much of the Plains grasslands, the presence of a mild spring and a moist, hot summer allow for coexistence of C_3 and C_4 grass floras, although a dynamic ebb and flow is apparent from year to year. During moist, mild springs and dry summers, C_3 grasses do well at the expense of C_4; by contrast, in years with dry springs and wet summers, the C_4 species become more competitive (Monson *et al.*, 1983).

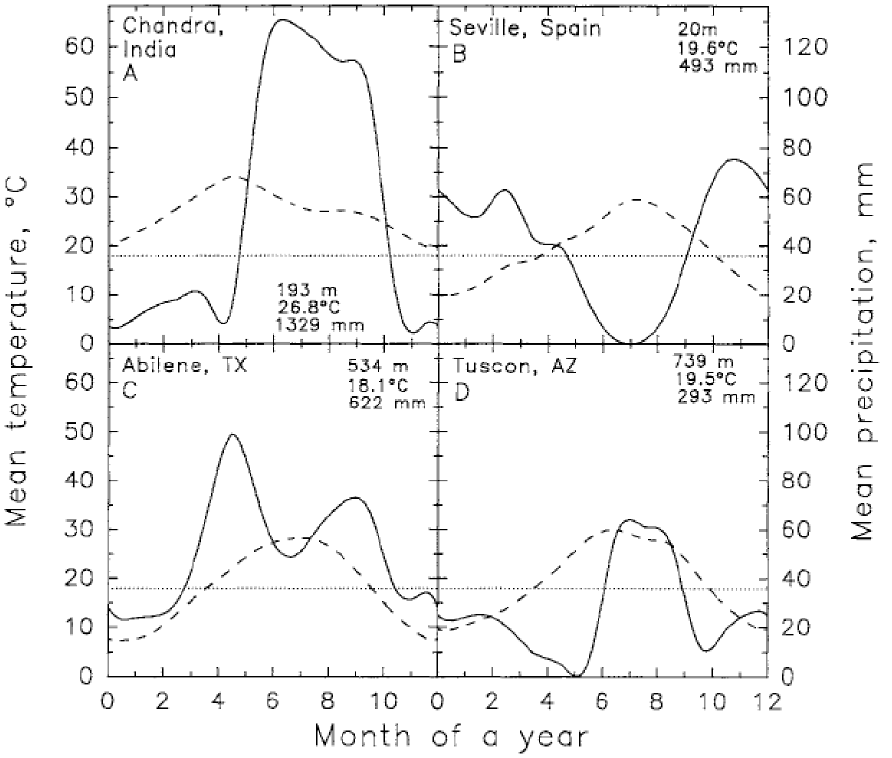


Figure 11 Climate diagrams for regions discussed in the text. (A) Chandra, central India, representative of a monsoonal climate with a hot, wet summer and a cool dry season. C_4 grasses dominate (>90%) the grass flora and production in open areas. (B) Seville, Spain, representative of a Mediterranean climate with a moist cool season and dry warm season. C_3 grasses dominate the grass flora and primary production. (C) Abilene, Texas, warm temperate grassland where the warm season is long enough (6 months over 18°C and wet enough to allow for C_4 dominance. (D) Tuscon, Arizona, a hot desert where distinct cool and hot seasons of precipitation allow for a temporally segregated C_3 and C_4 flora to coexist in the region. The precipitation is represented with a solid line and the temperature with a dashed line. Climate diagrams adapted from Walter et al. (1975). Elevation (Elev.), mean annual temperature (MAT), and mean annual precipitation (MAP) are shown for each climate station (Sage et al., 1999).

If climate conditions consistently favor one photosynthetic type over the other, then it can capture the necessary soil resources and dominate the site. In the plains of Texas, for example, long, hot summers with an abundance of summer precipitation (Figure 11C) consistently allow for aggressive summer growth of the C_4 dominants.

Whereas winter temperatures are mild enough to allow C_3 species to continue activity, the C_4 grasses produce a dense turf that captures space and nutrients to such an extent that cool season grasses are often excluded from the prairie (Tieszen *et al.*, 1997). This leads to an interesting phenomenon in North America where southern, C_4-dominated grasslands green-up at the same time of year as northern, C_3 dominated grasslands (Tieszen *et al.*, 1997). Alternatively, if climates do not allow for complete space and resource capture by one photosynthetic type, then temporally segregated C_4 and C_3 communities can coexist. This is observed in the Sonoron and Chihuahuan deserts of North America, where winter rains favor a C_3 flora of annual plants, whereas summer rains favor a rich C_4 annual flora (Figure 11D) (Kemp, 1983). Because of severe drought between the winter and summer seasons, moisture is insufficient to enable one community to persist for very long, and thus dominance is prevented.

3.1.5 Temperature

Growth and development of plants is usually taken as a function of accumulated heat above some threshold value, the so-called temperature sum. The sensitive part of grass for the temperature perception is the intercalary meristem and associated leaf base region in grass shoots. During the vegetative and early reproductive phases of growth the stem apex (shoot apex, apical meristem, growing point) in perennial ryegrass (*Lolium perenne*, C_3) is found on a series of short internodes at the base of the tiller. In spring (Northern Hemisphere, NH) the shoot apices are 9 mm below the soil surface and in the autumn 3 mm above (Peacock, 1975). As shown in Figure 12 the growth of *Lolium temulentum* (summer annual, C_3 grass species), ceases at 0 °C. Real stop of growth is a little below a temperature of zero and regain of growth is a little above a temperature of zero degrees.

Grass species and varieties differ in the rate of leaf growth. It seems that varieties with larger growth rates under winter conditions (NH) are more susceptible for frost damage. In February the elongation of the shoot apex by 10 mm may place the apex from 5 mm below (temperature –2 °C) to 5 mm above the soil surface with a lethal temperature of –15 °C (Peacock, 1975).

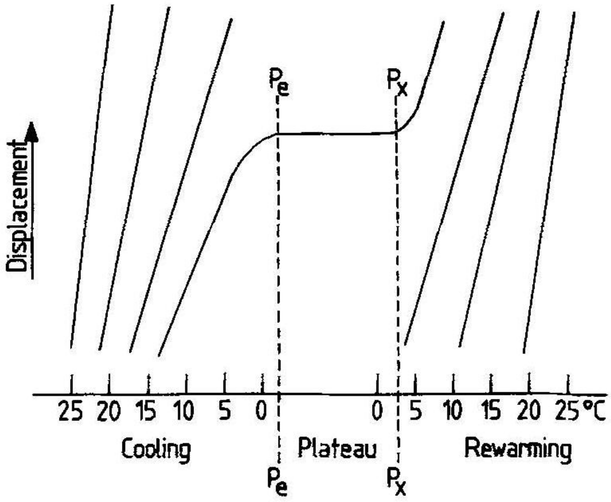


Figure 12 Growth (displacement) of leaf tip of a grass plant against time during a cycle of cooling and heating applied to the leaf base region of Lolium temulentum. P_e *and* P_x *refer to the temperature at which growth ceases during cooling and resumes during rewarming, respectively (Stoddart et al., 1986).*

3.1.6 Phenology

Physiological plant age is defined by development stage, which is characterized by formation of various organs and their appearance. The most important phenological change is from vegetative to reproductive stage, which determines a large redirection of dry matter allocation over the plant organs. As many physiological and morphological processes change with phenological stage, its accurate quantification is essential in any crop grow simulation model. For many annual crops, the development stage can conveniently be expressed in a dimensionless variable, having the value 0 at seedling emergence, 1 at flowering and 2 at maturity (Van Heemst, 1986).

The development of a plant is closely related to the temperature and it is common practice to calculate the phenology by dividing the temperature sum (degree-days) by the total temperature sum needed for maturity. The temperature sum is the accumulated temperature from day one when the temperature rises above a certain threshold.

((minimum temperature + maximum temperature)/2) – threshold temperature

In LPJmL, the phenology may have a value between 0 (sowing) and 1 (maturity, harvest). The calculation of the phenology of grass in LPJmL is described in 4.3.4.

3.1.7 Fire

Besides human activities related to urban living and agricultural production, fire is the most widespread ecological disturbance in the world. From the arctic boreal forests to the tropical grasslands and savannas of the world, fire destroys enormous quantities of plant biomass. It has been estimated that 2700-6800 million tons of plant carbon are consumed annually through the burning of savanna vegetation and through its use in shifting agriculture.

Fire is a widespread seasonal phenomenon in Africa. South of the equator, approximately 168 million hectares burn annually, nearly 17% of a total of 1014 million hectares, accounting for 50% of this total, with the remainder caused by the burning of firewood, agricultural residues, and slash from land clearing. Fires are started by both lightning and humans, but the relative share of fires caused by human intervention is rapidly increasing. Pastoralists use fire to stimulate grass growth for livestock, while subsistence agriculturalists use fire to remove unwanted biomass when clearing agricultural lands, and to eliminate unused agricultural residues after harvest. In addition, fires fueled by wood, charcoal or agricultural residues are the main source of domestic energy for cooking and heating (Goldammer & De Ronde, 2004). In most African ecosystems, fire is a natural disturbance of vegetation structure and composition, and in nutrient recycling and distribution.

Fire flourishes because most of sub-Sahara Africa has an environment to sustain it. There exists a chronic rhythm of wetting and drying. Seasonality follows a cadence of rainfall, not temperature. In wet seasons, the fuel load grows; in dry ones, these fuel loads may burn. Across this annual rhythm, longer waves of drought and deluge rise and fall. The onset of the rainy season will bring scattered thunderstorms and lightning which can set fire everywhere except for the driest (no fuel) or wettest (no combustion) sites.

This reinforces the fundamental conclusion that fire is a general and influential ecological phenomenon throughout the world (Bond & Van Wilgen, 1996). It cannot be ignored when considering the management of rangeland ecosystems for both, domestic livestock and wildlife purposes.

The role of fire in Africa, south of the Sahara, ranges from ‘a rare feature’ in both the driest regions (e.g. in the arid Karoo biome and semi-deserts) and in the wettest regions (e.g. in wet mountainous forests), to a yearly or two-yearly occurrence (e.g. in moist mountainous dynamic’ grasslands). In some biomes, human-caused fire is the most important factor affecting plant communities (e.g. in savannas of West Africa), while in others lightning fires are more common (e.g. in humid Equatorial areas (Mounkeila, 1984, Swaine, 1992). In most of the other biomes in sub-Saharan Africa, fires are caused mostly by lightning and anthropogenic sources.

Fire plays an important role in the dynamics of forests. Fire behavior determines the pattern of forest in the landscape. Forest species vary in their response to fire, and, for forest species, depend on fire for regeneration (Geldenhuys, 1994). In general, frequent fires will destroy mixed evergreen forest, but the occasional fire rejuvenates forest. In any one area, one could relate forest with very low fire frequencies and grassland with very high (sometimes annual) fire frequencies, with woodland and shrubland having intermediate long to short fire frequencies. In Africa, fire has extended the grasslands and savannas at the expense of evergreen forests (Pyne *et al.*, 2004).

Grasses survive fire that destroys the dry stems and leaves because the grasses' deep roots remain unharmed. The roots contain starch reserves for new growth when the soil becomes moister. The shrubs can also subsist on food reserves in their roots. Unlike grasses and shrubs, trees survive a fire by retaining some moisture in all their aboveground parts throughout the dry season. Some trees have a corky bark or semi succulent trunk covered with smooth resinous bark, both being fire resistant (http://www.ucmp.berkeley.edu/exhibits/biomes/grasslands.php ; Pullen & Ballard, 2004).

3.1.8 Vegetation of (sub) tropical grasslands

In (sub) tropical grasslands, the predominant vegetation consists of grasses and forbs (small broad-leaved plants that grow together with grasses). Different savannas support different grasses due to disparities in rainfall and soil conditions (example of savanna Figure 13). Because the savanna supports such a large number of species competing for living space, usually only one or a few kinds of grass are more successful than the others in a particular area. For example, in drier savannas such as those on the Serengeti plains or Kenya's Laikipia plateau, the dominant grasses on well-drained soils are Rhodes grass and red oat grass (Figure 14 and 15); throughout the East African savannas, star grasses (Figure 16) are dominant; the lemon grasses are common in many western Uganda savannas. Deciduous trees and shrubs are scattered across the open landscape. One type of savanna common in southwestern Kenya, Tanzania, and Uganda, known as grouped-tree grassland, has trees growing only on termite mounds the intervening soil being too thin or poorly drained to support the growth of trees at all. (http://www.ucmp.berkeley.edu/exhibits/biomes/grasslands.php#temp).

Figure 13 Savanna in the Samburu Game Preserve, Kenya. *(*http://www.eoearth.org/article/Grassland_biome *Source: University of California Museum of Paleontology)*

Figure 14 Rhodes grass (Chloris gayana Kunth)
(http://www.dpi.nsw.gov.au/__data/assets/image/0007/202021/rhodes-grass.jpg) and (http://www.dpi.qld.gov.au/images/Biosecurity_GeneralPlantHealthPestsDiseaseAndWeeds/Rhodes-Grass-Mature-250_rdax_168x202.jpg)

Figure 15 Red oat grass

(http://www.plantzafrica.com/planttuv /plimagestuv/themedatri3.jpg).

Figure 16 Star grass (Cynodon dactyon L.)
http://www.mobot.org/gardeninghelp/images/low/H200-0901020.jpg

Figure 17 Lemon grass (Cymbopogon flexosus)
(http://www.healthalternativesonline.com/lemongrass.html)

3.1.9 Vegetation of temperate grasslands

In temperate grasslands, perennial grasses and perennial forbs are dominant growth forms. Examples of perennial forbs are Compositae (or Asteraceae, depending on the taxonomic system used) and Leguminosae–the sunflower and pea families, respectively.

Perennial grasses, with their growth buds at or just below the surface, are well adapted to drought, fire and cold. The tiller or narrow, upright stem reduces heat-gain in the hot summers; the intricate root systems trap moisture and nutrients. Two basic types are:

- Turf- or sod-forming grasses, with rhizomes or underground stems from which new plants spring forth; associated with the more humid grasslands
- Bunch grasses, without rhizomes, that reproduce by seed; associated with the drier parts of the biome.

Temperate grasslands can be further subdivided in prairies and steppes. Prairies (Figure 18) are grasslands with tall grasses while steppes are grasslands with short grasses. Few natural prairie regions remain because, most have been turned into farms or grazing land. This is because they are flat, treeless, covered with grass, and have rich soil.

Steppes (Figure 19) are dry areas of grassland with hot summers and cold winters. They receive 25–51 cm of rainfall a year. Steppes occur in the interiors of North America and Europe. Plants growing in steppes are usually greater than 30 cm. They include blue grama (Figure 20) and buffalo grass (Figure 21), cacti, sagebrush, spear grass (Figure 22) and flowers including asters, blazing stars, coneflowers, goldenrods, sunflowers, clovers, psoraleas, and wild indigos. However, a few trees, such as cottonwoods, oaks, and willows grow in river valleys, and some nonwoody plants, specifically a few hundred species of flowers, grow among the grasses
(http://www.ucmp.berkeley.edu/exhibits/biomes/grasslands.php#temp).

Figure 18 The Konza tallgrass prairie in the Flint Hills of northeastern Kansas (2005 photo by Edwin Olson) http://en.wikipedia.org/wiki/Grassland#Tropical_and_subtropical_grasslands*.*

Figure 19 Example of steppes of Soviet Union (E. Benders-Hyde, http://www.blueplanetbiomes.org/steppe.htm*)*

Figure 20 Blue grama grass (Bouteloua gracilis)
http://www.outsidepride.com/images/ products/detail/pasture/bluegrama.jpg
and seedhead http://www.grasslands-bioblitz.org/Images/blue_grama_grass.jpg

Figure 21 Buffalo grass (Paspalum conjugatum Bergius)
http://luirig.altervista.org/cpm/albums/ 02a/000520-paspalum-paspaloides.jpg *and*
http://upload.wikimedia.org/wikipedia/commons/6/6d/Starr_070306-5134_Paspalum_conjugatum.jpg

Figure 22 Spear grass (Heteropogon contortus (L.) P. Beauv. ex Roemer & Schultes (http://www.agmates.com/blog/wp-content/uploads/2008/02/spear-grass.jpg)

Today, people use steppes to graze livestock and to grow wheat and other crops. Overgrazing, ploughing, and excess salts left behind by irrigation waters have harmed some steppes. Strong winds blow loose soil from the ground after ploughing, especially during droughts. This causes the dust storms of the Great Plains of the U.S. (http://www.ucmp.berkeley.edu/glossary/gloss5/biome/grassland.html).

3.2 Grassland biodiversity and conservation

Grasslands dominated by unsown wild-plant communities (unimproved grasslands) can be called either natural or 'semi-natural' habitats. The majority of grasslands in temperate climates are 'semi-natural'. Although their plant communities are natural, their maintenance depends upon anthropogenic activities such as low-intensity farming, which maintains these grasslands through grazing and cutting regimes. These grasslands contain many species of wild plants - grasses, sedges, rushes and herbs - 25 or more speerican prairie grasslands or lowland wildflower meadows in the UK are now rare and their associated wild flora equally threatened. Associated with the wild-plant diversity of the "unimproved" grasslands is usually a rich invertebrate fauna. There are also many grassland specialists among bird species, such as the snipe and the Great Bustard. Agriculturally improved grasslands, which dominate modern intensive agricultural landscapes, are usually poor in wild plant species due to the original diversity of plants having been destroyed by cultivation, the original wild-plant communities having been replaced by sown monocultures of cultivated varieties of grasses and clovers, such as Perennial ryegrass and White Clover. In many parts of the world, "unimproved" grasslands are one of the most threatened habitats, and a target for acquisition by wildlife conservation groups or for special grants to landowners who are encouraged to manage them appropriately (http://en.wikipedia.org/wiki/Grassland#Human_impact_and_economic_importance).

3.3 Definition of production grassland (this report)

In its narrow sense, “grassland” may be defined as ground covered by vegetation dominated by grasses, with little or no tree cover; UNESCO defines grassland as “land covered with herbaceous plants with less than 10 percent tree and shrub cover” and wooded grassland as 10-40 percent tree and shrub cover (White, 1983). Grassland in its wider sense of may be “grazing land”. Definitions of grassland and the associated term “range” are multitude, many with specific local legal connotations; the Second Expert Meeting on Harmonizing Forest-related Definitions for use by Various Stakeholders (FAO, 2000) gives eleven pages of them. The Oxford Dictionary of Plant Sciences (Allaby*,* 1998) gives a succinct definition:

“Grassland occurs where there is sufficient moisture for grass growth, but where environmental conditions, both climatic and anthropogenic, prevent tree growth. Its occurrence, therefore, correlates with a rainfall intensity between that of desert and forest and is extended by grazing and/or fire to form a plagioclimax in many areas that were previously forested.” (Reynolds, 2005).

The emphasis of this report is on production grassland with the following definition is used to classify land as production grassland:

Production grassland is an area where grassland exists for more than five years.

Furthermore, it is assumed that production grassland exists in areas where animals like dairy cows, cattle, goats, sheep, horses, donkeys and camels are held according to the FAO maps.

3.4 Grasslands in LPJmL

Natural grassland exists due to environmental characteristics like temperature, moisture and availability of nutrients (Fig. 23). In LPJmL, the main characteristics like temperature, moisture and fire are taken into account to calculate the grass production (gray parts in Figure 23).
In the following sections, these characteristics are discussed to some extent.

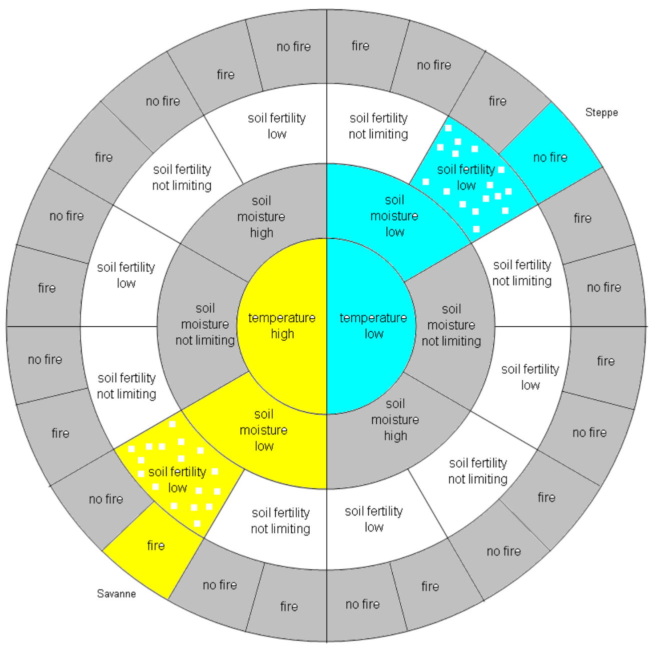


Figure 23 Environmental characteristics influencing the suitability of vegetations (grass).

4 Short description of LPJmL with emphasis on grass

4.1 Introduction

The model LPJmL is based on the Lund-Potsdam-Jena Dynamic Global Vegetation Model. LPJmL means Lund-Potsdam-Jena managed land, which simulates carbon and water cycles of natural vegetation and productivity and carbon yield of the most important crops worldwide. The calculations are based on biophysical and biochemical processes (Bondeau *et al.*, 2007). Within grid cells of 0.5° (approximately 50 x 50 km), the yield of nine plant functional types (PFT) and eleven crop functional types (CFT) are simulated. C_3 and C_4 grasses are distinguished as two different PFT. The model simulates a stand for each cell. A stand may consist of one PFT or CFT or a combination of plant functional types and/or crops. The simulation for each grid cell begins from "bare ground", requiring a "spin up" (under non-transient climate) of 1000 years to develop equilibrium vegetation and soil structure (lpj.h). For test runs with grassland, a spin up of 30 years is enough to stabilize the annual net ecosystem productivity (NEP) (g C m^{-2}).

There are two major aspects of the model to be distinguished:
1) the grid (environmental characteristics) and
2) the biophysics of the crop or plant functional type (grass in this case).

4.2 Environment and climate

Each cell is identified with a cell or grid number and has a specific latitude and longitude. With the location of the cell (latitude and longitude), the day length and the net downward short-wave radiation flux is calculated. For every cell, input tables for monthly mean air temperature, total precipitation and percentage of full sunshine, annual atmospheric CO_2 concentration and soil texture class are available. The daily temperatures and precipitation are interpolated from the monthly values. With these environmental parameters, the potential evapotranspiration, snow and soil temperature are calculated (Sitch *et al.*, 2003). These data are necessary to calculate the gross potential carbon production in a particular grid cell.

One of the most important environmental properties for the photosynthesis (and plant production) is the photosynthetically active radiation. This is the topic of the next section.

4.2.1 Photosynthetically active radiation (PAR)

The plant uses the photosynthetically active radiation (PAR in MJ $m^{-2}d^{-1}$) to convert CO_2 into carbohydrates. In LPJmL, the PAR is given as an input table. To check the values of the input table a comparison is made with the PAR of another grass-growing model named LINGRA. This model is chosen because it is well described, tested and proven valid and reliable for European conditions (Schapendonk *et al.*, 1998).

In LPJmL, the PAR is calculated according to Prentice *et al.* (1993) and is calculated as:

$$PAR = \left(\frac{0.5}{e^*}\right) R_s$$

The parameter *PAR* is 50% of R_s, the daily net short wave radiation flux in MJ d^{-1}. The parameter e^* is the conversion factor to molar units and has a value of 0.27 MJ Mol^{-1}.

The daily net radiation R_n is the daily net shortwave flux R_s minus the daily net upward long wave flux R_l:

$$R_n = R_s - R_l$$

The parameter R_s is calculated as (Linacre, 1968); Prentice *et al.*, 1993)):

$$R_s = z(c + d * n_i)(1 - \beta)Q_0$$

c =0.25 (–)
d =0.5 (–)
β =0.17 (–)

The parameters c and d are empirical constants calculated by Friend (1996) from a regression of the ratio of measured to potential radiation versus the percentage of maximum possible sunshine hours. The variable n_i is the proportion of possible hours of bright sunshine and the parameter β is the shortwave albedo set to an average value of 0.17 (Prentice *et al.*, 1993)

$$Q_0 = 3600 Q_{00}\left[1 + 2 * 0.01675 \cos\left(\frac{360 * i}{365}\right)\right]$$

where

Q_{00} is the solar constant (1360 W m^{-2}) and
i is the day number (from 1–365 starting at January 1).

$$z = u * h + v * (24/2\pi)\sin\left(\frac{360 * h}{24}\right)$$

$$u = \sin(l)\sin(\delta)$$

$v = \cos(l)\cos(\delta)$ where l is latitude,

$$\delta = -23.4^o \cos\left[\frac{360(i + 10)}{365}\right]$$

and h is the day length in hours, calculated as:

$$h = 0 \quad u \le v$$

$$h = 24\left[\frac{a\cos\left(\frac{-u}{v}\right)}{2\pi}\right] \quad u > -v, u < v$$

$$h = 24 \;\; u \ge v$$

When the location and time for both models, LPJmL and LINGRA, are the same, it is to be expected that the values of their *PAR* are equal.

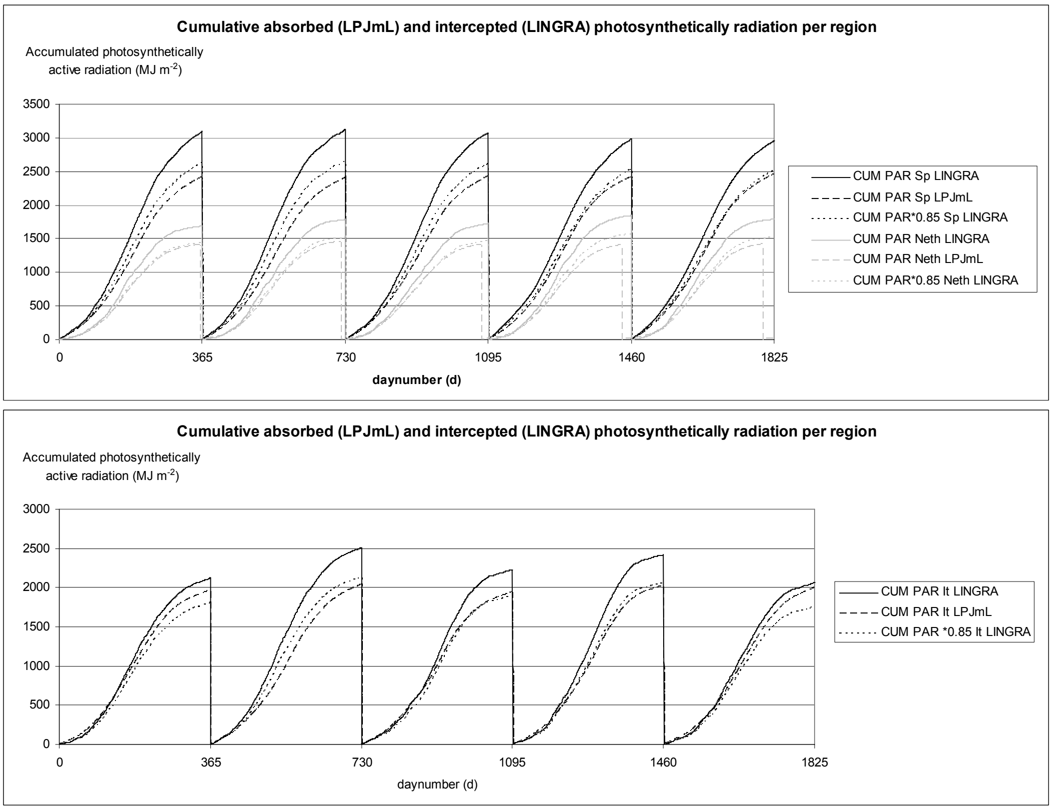


Figure 24 Accumulated absorbed (LPJmL), intercepted (LINGRA) photosynthetically active radiation (MJ m^{-2}*) and intercepted photosynthetically active radiation of LINGRA times 0.85 per day for Spain, the Netherlands and Italy.*

In LPJmL the absorbed *PAR* is used and in LINGRA the intercepted *PAR*. In theory approximately 85% of the intercepted *PAR* is absorbed (Sinclair & Muchow, 1999) and 15% of the intercepted *PAR* is reflected (Figure 24). When this is taken into account, the *PAR* of both models match.

The parameter name *PAR* is used in both models although the meaning is different.
Similar names with a different meaning are quite common in modeling, but model comparison can only be done properly if units and meaning of variables are provided.

4.2.2 Absorbed photosynthetically active radiation (APAR)

In LPJmL, the photosynthesis is calculated as a function of absorbed photosynthetically active radiation (*APAR*). The *APAR* (J $m^{-2}d^{-1}$) is calculated from the (absorbed) photosynthetically active radiation (*PAR*, J $m^{-2}d^{-1}$) multiplied by the fraction of incoming PAR intercepted by green vegetation (*FPAR*, –) and $alpha_a$ (–) (Haxeltine & Prentice, 1996a).

$$APAR = FPAR * PAR * alpha_{\mathrm{a}}$$

FPAR is described in more detail in section 4.2.3. In section 4.2.4, the parameter $alpha_a$ is discussed.

In LINGRA (Wolf, 2006), the total intercepted photosynthetically active radiation (MJ m^{-2} d^{-1}) *PARINT* is calculated as the fraction of light interception, *FINT* (–) times the photosynthetically active radiation, *PAR* (MJ $m^{-2}d^{-1}$) as:
PARINT = FINT*PAR

The difference between the two approaches is the parameter $alpha_a$ used in LPJmL.

4.2.3 Fraction of intercepted incoming PAR (FPAR)

The parameter *FPAR* (–) is the fraction of intercepted incoming *PAR* by green vegetation and is calculated as the phenology times the foliage projective cover (*FPC*) (see 4.3.4 about phenology).

FPAR = phen * FPC   (–)

The parameter *FPC* is calculated according to Beer's law (Equation 4, Haxeltine & Prentice, 1996a) using the leaf area index (*LAI*) and the extinction coefficient (*k*).

$$FPC = nind * (1 - e^{(-kLAI)}) \qquad (–)$$

nind is the individual density (amount of individual plants m^{-2}ground) has a permanent value of 1 for grassland.

k = 0.5 extinction coefficient (m^2 ground m^{-2} leaf)
LAI = leaf area index (m^2 leaf m^{-2} ground)

The parameter `nind` plays a role when trees and shrubs are part of the grids vegetation but not when the grid is covered with grasses only. In the equation of *FPC*, the nind should be without dimensions or units. In LINGRA, the amount of tillers m^{-2} is used to calculate the rate of sink limited leaf growth but it has no role in the fraction of light interception (*FINT*). The extinction coefficient *k* varies considerably among different plant species based on plant structure and it depends on the angle of the sun (Larcher, 1983). In LPJmL, an average value of *k* (0.5) appropriate for modeling photosynthesis at large scales is used (Woodward, 1987). The experimental value of the extinction coefficient *k* in LINGRA is 0.6–07. Because of the use of absorbed *PAR* rather than intercepted *PAR* in LPJmL, the extinction coefficient may have a somewhat lower value in LPJmL.

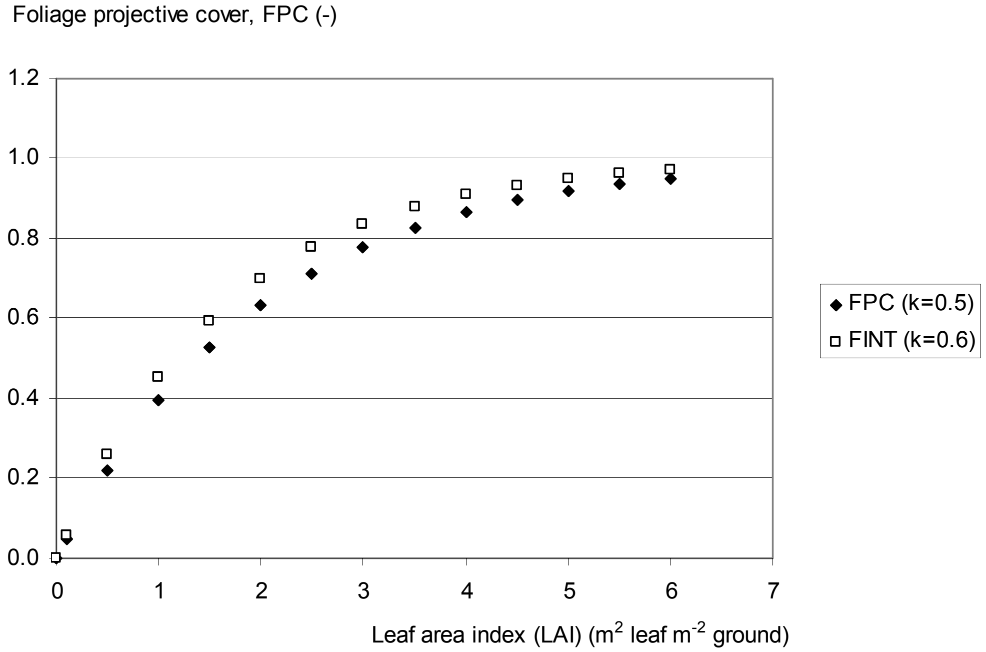


Figure 25 Foliage projective cover depending on leaf area index using an extinction coefficient of 0.5 (as in LPJmL) and 0.60 (as in LINGRA).

In Figure 25 an example of the FPC according to LPJmL and LINGRA as a function of *LAI* are given. Although the functions used for the calculation of FPC in LPJmL and FINT in LINGRA are similar, it is difficult to compare these parameters because of difference in *LAI* calculation. In both models, the amount of carbon in the leaves (and the *SLA*) determines the *LAI* but this parameter is calculated in a very different way see subsection 4.3.5.4 for the calculation of carbon in the leaves and section 4.3.7 for the calculation of the *LAI*.

4.2.4 Alpha$_a$

According to Haxeltine and Prentice (1996a), $alpha_a$ is an empirical parameter that accounts for reductions in *PAR* utilization efficiencies in natural ecosystems and is assigned a value of 0.5 based on quantum efficiencies from field and laboratory measurements (Haxeltine & Prentice, 1996b and not in Landsberg, 1986 as Haxeltine and Prentice reported in 1996a). Haxeltine and Prentice (1996a) use $alpha_a$ as a scaling parameter to reduce the primary production of natural ecosystems.

The parameter $alpha_a$ reduces the calculated gross carbon (biomass) production and therefore acts as a management factor resulting in the calculation of the actual production rather than the gross potential carbon production. In Figure 26 the effect of the value of $alpha_a$ on accumulated carbon is given. The amount of accumulated carbon is higher when the value of $alpha_a$ is one instead of the default value 0.5 for natural vegetation. For crops $alpha_a$ has value one. It seemed that the idea of $alpha_a$ as a management factor already had its influence in the programming of the LPJmL model. The name of $alpha_a$ changes from alpha to `alphaa_manage` to `alphaa_grass` (this is allowed in the computer language C where this version of LPJmL is programmed in, although this is confusing for the user).

The use of factor $alpha_a$ has implications when the results of calculated carbon production are compared with experimental data. LPJmL can calculate the gross potential carbon production because an option for irrigation can be chosen. For the calculation of the carbon production of grass with LPJmL, the option for irrigation is switched off and the water-limited carbon production is calculated rather than the potential carbon production. Although the parameter $alpha_a$ has kept its value of 0.5 during the test runs, the results of LPJmL for grass are called water-limited carbon production in the remainder of the report instead of actual production. The calculation of the plant production will be described in 4.3.

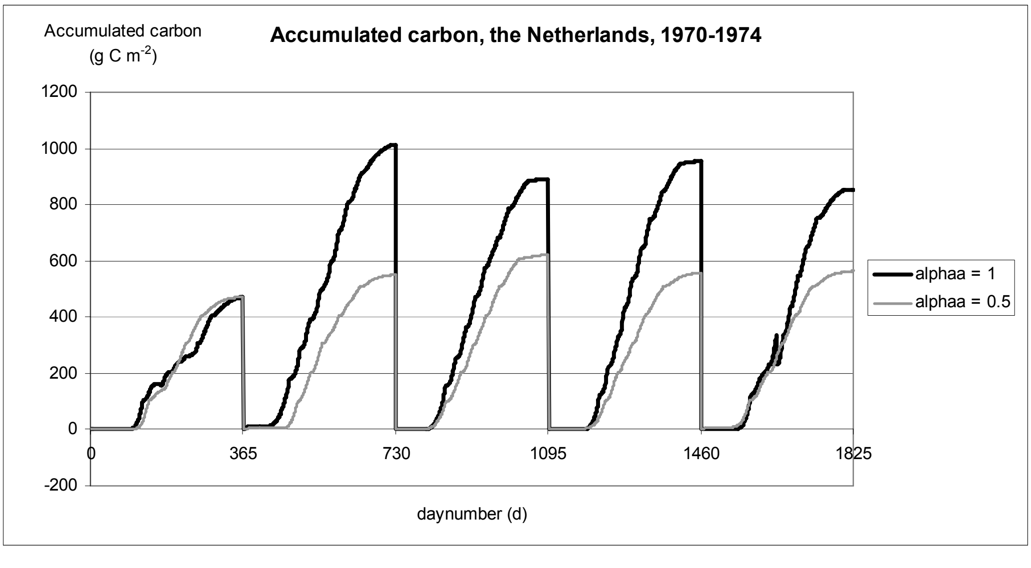


Figure 26 Example of the effect of the value of alpha$_a$ (0.5 (default in LPJmL) or 1) on the accumulated carbon calculated for the Netherlands from 1970-1974.

4.3 Plant production

When the environmental data are imported in the LPJmL model, there is an option to run a spin up first. This generates stable weather conditions for every grid. After the spin up LPJmL continues with the calculation of the gross primary production (gpp, g C $m^{-2}d^{-1}$) based on Farquhar. Subtracting the gross primary production with the amount of carbon in respiration losses gives the net primary production (npp, g C $m^{-2}d^{-1}$). Using the soil water balance and sensitivity of the carbon production to water stress, the water-limited production is calculated. The difference between the water-limited and the actual production is a gap that needs to be explained with management factors like nutrients and pests and diseases (chapter 6), but these factors are not admitted in LPJmL.

As mentioned before, at some places in the report a comparison will be made with the grass growth model LINGRA. To be able to compare the dry matter production per m^2 of LINGRA, the carbon production per m^2 of LPJmL is divided by 0.45 g C g^{-1} dm. In the next section, the calculation of the gross carbon production reported by Haxeltine & Prentice (1996a) is given with the corresponding description or code in LPJmL.

4.3.1 Gross carbon production

In LPJmL, the gross carbon production is calculated on a daily basis (g C $m^{-2}d^{-1}$) according to Farquhar (Haxeltine & Prentice, 1996a). The daily gross photosynthesis A (or agd in LPJmL) depends on a gradual transition between two limiting rates: J_E, describing the response of photosynthesis to absorbed photosynthetically active radiation (*APAR*) under *PAR* limitation (Haxeltine & Prentice, 1996b) and J_C, describes the Rubisco limited rate of photosynthesis (Haxeltine & Prentice, 1996; Collatz *et al.*, 1991). To describe the transition between the two rates J_E and J_C, the nonrectangular hyperbola formulation is used (Haxeltine & Prentice, 1996a and b).

$$\theta A^2 - (J_C + J_E)A + J_E J_C = 0$$

The solution for A:

$$A = \left(\frac{J_C + J_E - \sqrt{(J_C + J_E)^2 + 4\theta J_E J_C}}{2\theta} \right)$$

The empirical parameter θ (–) describes the transition between the two limiting rates J_E and J_C, and may be experimentally determined (Haxeltine & Prentice, 1996a). In LPJmL, this parameter is `theta` (–). The parameters used in the LPJmL code and described in the literature are given in Table 6 and Table 7.

Calculation of J_E and je

J_E, the PAR–limited photosynthesis rate (g Cm^{-2} d^{-1}) (Haxeltine & Prentice, 1996a) is calculated as:

$$J_E = C1_{C3} APAR \qquad (\text{g C m}^{-2}\text{d}^{-1})$$

The parameter *APAR* (Mol photons $m^{-2}d^{-1}$) is the absorbed *PAR*.

In LPJmL code:

`je=c1*apar*cmass*cq/daylength` (g C $m^{-2}h^{-1}$)

`c1`	the amount of carbon produced per mol photons (Mol C Mol^{-1} photons)
`apar`	is the absorbed part of PAR (J $m^{-2}d^{-1}$) (see section 4.2.1).
`cmass`	molar mass of carbon (g C mol^{-1}C)
`cq`	`4.6e-6` is the conversion factor for solar radiation at 550 nm from J m^{-2} to E m^{-2} (E mol quanta) (mol J^{-1})
`daylength`	is 24 (h day^{-1})

Differences between Haxeltine and Prentice (1966a) and LPJmL are:

- the J_E of Haxeltine and Prentice (1966a) is calculated per day and in LPJmL the `je` is calculated per hour,
- the energy unit of *APAR* in Haxeltine and Prentice (1996a) is amount of photons and in LPJmL the energy unit of `apar` Joules.

This has consequences for the units of the conversion factor from radiation to carbon (Cl_{C3} and `c1`).

Calculation of $C1_{C3}$ and `c1`

The parameter $C1_{C3}$ (Haxeltine & Prentice, 1996a) gives the carbon production per mol photons of the photosynthetically active radiation.

$$C1_{C3} = \Phi_c \Phi_{TC3} C_{mass} \alpha_a \alpha_{C3} \left[\frac{(p_i - \Gamma_*)}{(p_i + 2\Gamma_*)} \right] \quad \text{(g C mol}^{-1}\text{ photons)}$$

In LPJmL, the parameter c1 is the amount of carbon produced by the plant per amount of energy (J) from the photosynthetically active radiation.

In LPJmL code:

`c1=tstress*alphac3*((pi-gammastar)/(pi+2.0*gammastar))` (g C J–1)

In the LPJmL code the parameters Φ_C, C_{mass} and α_a are not used for the calculation of `c1`. The parameter Φ_C is a PFT specific parameter to account for the observation that maximum rates of photosynthesis for conifer needles decrease with increasing needle age and it has a value one (Haxeltine & Prentice, 1996a). The parameter C_{mass} is used as `cmass` in the calculation of the parameter `je` in LPJmL. The parameter α_a (–) is not used in the calculation of the photosynthesis at this place in the model, but in the calculation of the water-limited plant production and will be discussed in paragraph 4.2.4.

Calculation of Φ_{TC3} and tstress

The photosynthesis depends on the temperature and has a minimum, optimum and maximum temperature range, which is different for C_3 and C_4 plants. In Haxeltine and Prentice (1996a), the parameter Φ_{TC3} models the effect of low temperatures on C_3 photosynthesis, where T_c is the monthly temperature (°C).

$$\Phi_{TC3} = \frac{1}{1 + e^{[0.2(10 - T_c)]}} \quad (–)$$

In LPJmL the temperature stress (`tstress` or `temp_stress()`) is calculated in a more complex way and depends on the temperature, the day length, the minimum, optimum and maximum temperature for C_3 or C_4 photosynthesis (Figure 27 and Table 4), and the values of parameters `k1`, `k2` and `k3`.

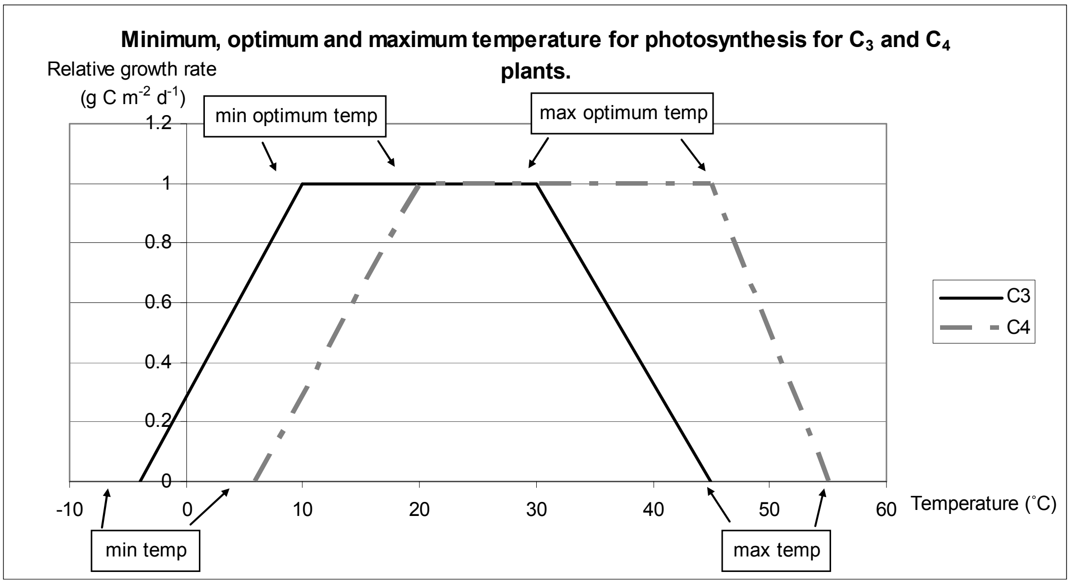


Figure 27 Relative growth rate and minimum, optimum and maximum temperature for photosynthesis for C_3 and C_4 plants.

Table 4 Minimum, optimum and maximum temperature (˚C) for photosynthesis for C_3 or C_4 plants (LPJmL).

	Parameter in LPJmL	**C_3**	**C_4**
minimum temperature	temp_co2.low	–4	6
minimum of optimum temperature	temp_photos.low	10	20
maximum of optimum temperature	temp_photos.high	30	45
maximum temperature	temp_co2.high	45	55

If the temperature is lower than the maximum temperature for photosynthesis two parameters are calculated: `low` and `high`.

low =1/(1+exp(k1*(k2–temperature)));
high =1–0.01*exp(k3*(temperature–max temperature for photosynthesis));

k1 = 2*ln(1/0.99–1)/ (min temp – min opt temp)
k2 = (min temp + min opt temp)*0.5
k3 = ln(0.99/0.01)/ (max temp – max opt temp)

These rules are written in the file `fscanpftpar.c` in LPJmL and the resulting values are given in Table 5.

Table 5 Values of k1, k2 and k3 for C_3 and C_4 plants.

	C_3	**C_4**
k1	0.656	0.656
k2	3	13
k3	0.306	0.459

The value of `low` times `high` is returned as the value of `tstress`.

```
tstress = low * high (-)
```

Although this way of calculating the temperature stress gives the flexibility to differentiate between C_3 and C_4 values but it is quite complex and may cause unnecessary confusion. When possible in C, it would be straighter forward to use a function like

FUNCTION Temp_photo = –4., 0., 10., 1., 30., 1., 45., 0. and the function call
REDTMP = AFGEN(Temp_photo,TEMP)

The FUNCTION statement determines a pairs of numbers (x,y points in the co-ordinate system) of the specified function.

In Figure 28, the calculated reduction of the photosynthesis in C_3 plants due to low temperatures according to the two methods (Haxeltine and Prentice, 1996a and LPJmL) are compared. The method according to Haxeltine and Prentice (1996a) has a decreasing temperature stress from –5 to 20°C and the method used in LPJmL has a decreasing temperature stress between –5 and 10°C. Causing a faster reduction of the temperature stress in LPJmL (at lower temperatures) than the temperature stress by Haxeltine and Prentice (1996a).

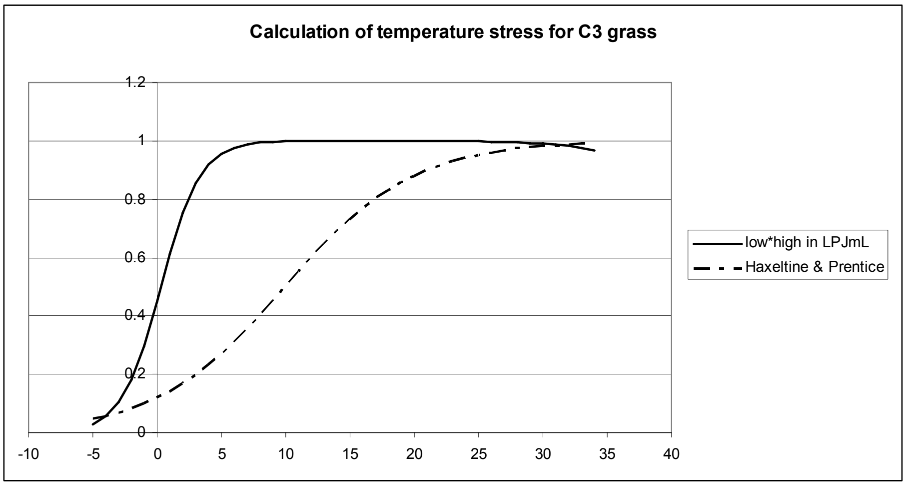


Figure 28 Calculation of the temperature stress by the method used by LPJmL and Haxeltine and Prentice (1996a) as a function of temperature for C_3 grasses.

The temperature stress at low temperature on C_4 grasses is given in part: Calculation of $C1_{C4}$.

Calculation of α_{C3} and `alphac3`

The parameter α_{C3} is the intrinsic quantum efficiency for CO_2 uptake as measured in laboratory studies and has a value of 0.08 (–) (Collatz *et al.* 1991). In LPJmL, this is the parameter `alphac3` with the same value. For α_{C4} see the part: Calculation of $C1_{C4}$.

Calculation of p_i and pi

The parameter p_i is the internal partial pressure of CO_2 given by:

$$p_i = \lambda p_a \text{ (Pa)}$$

The parameter p_a is the ambient partial pressure of CO_2. Under non-water stressed conditions, stomata respond in a way that maintains a constant ratio of intercellular (p_i) to ambient (p_a) CO_2 partial pressure of 0.6–0.8 (Wong *et al.*, 1979; Long & Hutchin, 1991). Haxeltine & Prentice (1996a) set λ equal to a maximum value (λ_{mC3}=0.7 (–)).

In the LPJmL code:
`pi=lambdamc3*co2` (see Table 6 for details)

In LPJmL, the `lambdamc3` has a value of 0.8 (–).

Calculation of Γ_* and `gammastar`

The parameter Γ_* is the CO_2 compensation point given by:

$$\Gamma_* = \frac{[O_2]}{2\tau} \quad \text{(kPa)}$$

The parameter $[O_2]$ is the partial pressure of oxygen (Haxeltine & Prentice, 1996a). The parameter τ is a ratio of kinetic parameters (-) describing the partitioning of RuBP to the carboxylase or oxygenase reactions of Rubisco (Collatz *et al.*, 1991). The parameter τ has a temperature dependency modeled by a Q_{10} relationship. The value of τ can be determined experimentally from gas exchange experiments on intact leaves (Brooks & Farquhar, 1985) and is 2600 (-); the Q_{10} value is 0.57.

In the LPJmL code, the same formula is used:

```
gammastar=po2/(2*tau)

tau=tau25*pow(q10tau,(temp-25)*0.1)
po2          20.9e3   O2 partial pressure in Pa
q10tau       0.57     q10 for temperature-sensitive parameter tau
tau25        2600.0   value of tau at 25 deg C (-)
temp                  is the daily temperature (˚C)
```

Calculation of J_C and `jc`

The parameter J_C, the of rubisco-activity-limited photosynthesis rate (mol C $m^{-2}h^{-1}$) (Haxeltine & Prentice, 1996a) is calculated as:

$$J_C = C2_{C3} V_m$$

The parameter $C2_{C3}$ is the ratio between the maximum daily photosynthesis rate and the actual photosynthesis rate (–).

The parameter V_m is the maximum daily rate of net photosynthesis (g C $m^{-2}d^{-1}$)

In LPJmL code:

```
jc=c2*hour2day(vm)
```

`hour2day` (0.04167 = 1/24) is a conversion factor from hour to day (d h^{-1})
`vm` is the maximum daily rate of net photosynthesis (g C $m^{-2}d^{-1}$)

Calculation of $C2_{C3}$ and c2

$$C2_{C3} = \frac{(p_i - \Gamma_*)}{\{p_i + K_c(1+[O_2]/K_o)\}}$$ (–)

K_c, K_o and τ are kinetic parameters whose temperature dependence is modeled using a Q_{10} relationship. The parameter K_o is the Michaelis-Menten constant for O_2 and K_c is the Michaelis-Menten constant for CO_2, the values and units are given in Table 6.
The parameters $[O_2]$ and p_i are already mentioned.

In LPJmL code:
```
c2 =(pi-gammastar)/(pi+fac) (-)

fac =kc*(1+po2/ko)

ko      = ko25*pow(q10ko,(temp-25)*0.1)
kc      = kc25*pow(q10kc,(temp-25)*0.1)
ko25    = 30 kPa with q10ko 1.2
kc25    = 30 Pa with q10kc 2.1
```

Calculation of V_m and `vm`

After calculation of $C1_{C3}$ and $C2_{C3}$ the model calculates the value of V_m. This optimal value of V_m is calculated by optimizing the formula for daily net photosynthesis rate using the constraint $\delta A_{nd}/\delta V_m=0$, resulting in the following equation for V_m (g C m^{-2} d^{-1}).

$$V_m = \left(\frac{1}{b_{C3}}\right)\left(\frac{C1_{C3}}{C2_{C3}}\right)\left[(2\theta - 1)s - (2\theta s - C2_{C3})\sigma\right]APAR$$

$$\sigma = \sqrt{\left[1 - \frac{(C2_{C3} - s)}{(C2_{C3} - \theta s)}\right]}$$

$$s = (24/d_t)b_{C3}$$

d_t is the day length (h).
b_{C3} is the ratio of the daily respiration of leaf rate and the maximum daily net photosynthesis rate (Farquhar *et al.*, 1980 (–) (see Table 6).

In LPJmL code:
```
vm=(1.0/bc3)*(c1/c2)*((2.0*theta-1.0)*s-(2.0*theta*s-c2)*sigma)
apar*cmass*cq

s       = (24/daylength)*bc3
sigma   = 1-(c2-s)/(c2-theta*s)
```

The difference between the calculation of V_m and `vm` are the `cmass` and `cq` parameters in LPJmL.

Calculation of R_d and `rd`

$$R_d = b_{C3}V_m$$

R_d is the daily respiration of leaf. In LPJmL, the `rd` is calculated after the calculation of $C1_{C4}$ and $C2_{C4}$.

Calculation of $C1_{C4}$ and `c1`

A model for C_4 photosynthesis was adapted from Collatz *et al.* (1992) (Haxeltine & Prentice, 1996a) using the same optimization procedure. For C_4 photosynthesis the functions $C1_{C3}$ and $C2_{C3}$ are replaced by $C1_{C4}$ and $C2_{C4}$ which are calculated as:

$$C1_{C4} = \Phi_{pi} \Phi_{TC4} C_{mass} \alpha_a \alpha_{C4}$$

In LPJmL code:
`c1=tstress*alphac4`

In the LPJmL code, the parameter `cmass` is used in the calculation of `je` and α_a is used in the calculation of the water-limited photosynthesis of C_4 grasses.

Calculation of Φ_{pi} and `phipi`

The parameter Φ_{pi} is the effect of reduced p_i on the C_4 photosynthesis rate.

$$\Phi_{pi} = \frac{\lambda}{\lambda_{mC4}} \quad (–)$$

The parameter λ_{mC4} (0.4 (–)) is the optimal ratio of intercellular to ambient CO_2 concentration in C_4 plants maintained under non-water-stressed conditions.
The parameter λ is the optimal Ci/Ca ratio.

In LPJmL code:
`phipi=lambda/lambdamc4` (–)

If `phipi` is smaller than one:
`c1=tstress*phipi*alphac4`

Calculation of Φ_{TC4} and `tstress`

The parameter Φ_{TC4} accounts for the approximate response of C_4 plants to extreme temperatures, following Collatz *et al.*, 1992.

$$\Phi_{TC4} = \frac{1}{1+\exp[0.3(13-T_c)]} * \frac{1}{1+\exp[0.3(T_c-36)]} \quad (–)$$

The parameter Φ_{TC4} is called `tstress` in LPJmL and is calculated in a different way than in Haxeltine & Prentice (1996a). The `k1`, `k2` and `k3` in LPJmL for C_4 plants are calculated in the same way as for C_3 plants with the according parameter values (Table 4).

In Figure 29 a comparison between the calculated temperature stress for C_4 plants according to Haxeltine and Prentice (1996a) and LPJmL is made. The methods coincide until 25 °C then Haxeltine decreases below one where the temperature stress in LPJmL stays one. There is no high temperature stress in LPJmL for C_4 grasses as there is according to Haxeltine and Prentice (1996a).

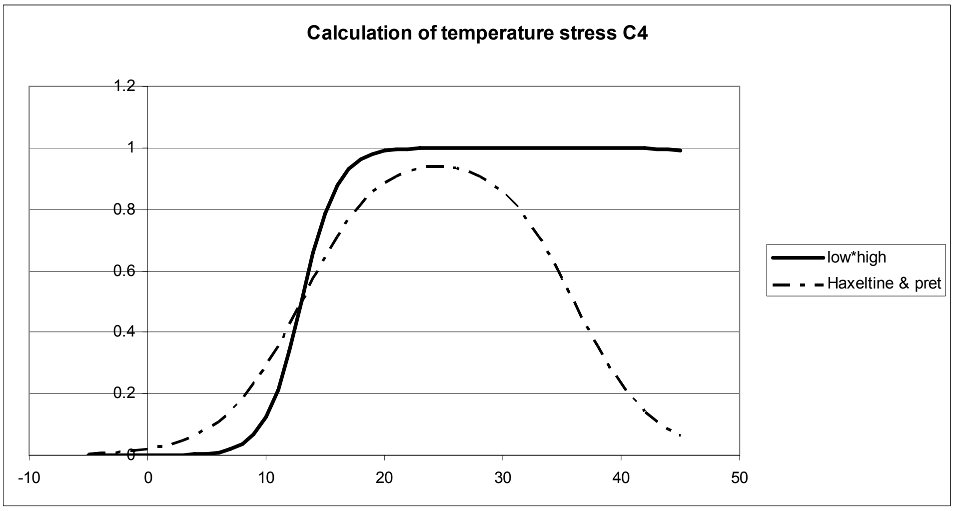


Figure 29 Calculation of the temperature stress by the method used by LPJmL and Haxeltine and Prentice (1996a) as a function of temperature for C_4 grasses.

Parameter α_{C4} and `alphac4`

The parameter α_{C4} is the intrinsic quantum efficiency for CO_2 uptake as measured in laboratory studies and has a value of 0.053 (–) (Ehleringer & Björkman, 1977).

In LPJmL, this is the parameter `alphac4` (Table 6) with the same value.

Calculation of parameter $C2_{C4}$

$$C2_{C4} = 1 \quad (\text{–})$$

Calculation of the maximum daily net photosynthesis rate (V_m) and `vm`

With the calculated $C1_{C4}$ and $C2_{C4}$, the `vm` can be calculated for C_4.

$$V_m = \left(\frac{1}{b_{C4}}\right)\left(\frac{C1_{C4}}{C2_{C4}}\right)\left[(2\theta - 1)s - (2\theta s - C2_{C4})\sigma\right]APAR$$

In LPJmL:

```
vm=(1.0/bc4)*c1/c2*((2.0*theta-1.0)*s-(2.0*theta*s-c2)*sigma)*apar*
   cmass*cq
```

Table 6 Values of parameters and constants used in the photosynthesis model (Haxeltine & Prentice, 1996a).

Symbol	**Value**	**Units**	**Q_{10}**	**Description**	**Source**	**In LPJmL**
θ	0.7	(–)		shape parameter	b, i	`theta`
Φ_c	1	(–)		agening parameter for maximum photosynthesis rate	a	–
	4.6e–6	mol J^{-1}		conversion factor for solar radiation at 550 nm from J m^{-2} to E m^{-2} (E mol quanta)		`cq`
C_{mass}	12	mol^{-1}		molar mass of carbon	a	`cmass`
α_a	0.5			scaling parameter for α	a	`alphaa`
α_{C3}	0.08			C_3 intrinsic quantum efficiency	e, d	`alphac3`
α_{C4}	0.053			C_4 intrinsic quantum efficiency	e	`alphac4`
	24	h day^{-1}				`daylength`
λ	0.8			optimal Ci/Ca ratio		`lambda`
	0.8			optimal ratio of intercellular to ambient CO_2 concentration (lambda) in C_3 plants	a	`lambdac3`
λ_{mC3}	0.7			optimal ratio of intercellular to ambient CO_2 concentration (lambda) in C_3 plants	a	
λ_{mC4}	0.4			optimal ratio of intercellular to ambient CO_2 concentration (lambda) in C_4 plants	a	`lambdac4`
$[O_2]$	20.9	kPa		partial pressure of O_2		`po2`
τ	2600		0.57	CO_2/O_2 specific ratio	c	`tau`
K_o	30	kPa	1.2	Michaelis-Menten constant for O_2	d	ko25 with q10ko for Q_{10} value
K_c	30	Pa	2.1	Michaelis-Menten constant for CO_2	d	kc25 with q10kc for Q_{10} value
b_{C3}	0.015	(–)		R_d/V_m ratio for C_3 plants	f	`bc3`
b_{C4}	0.035	(–)		R_d/V_m ratio for C_4 plants	a	`bc4`

a Haxeltine & Prentice, 1996a
b Haxeltine & Prentice, 1996b
c Brooks & Farquhar, 1985
d Collatz *et al.* ,1991
e Ehleringer & Björkman, 1977
f Farquhar *et al.*, 1980
g Long & Hutchin, 1991
h Wong *et al.*, 1979
i McMurtrie & Wang, 1993
j Sage, 1990

Table 7 Parameters used by Haxeltine and Prentice, 1996a and in the LPJmL model.

Symbol in a	Units	Description	Source	Symbol in LPJmL
agd	g C m^{-2}d^{-1}	daily gross photosynthesis		`agd`
And	g C m^{-2}d^{-1}	daily net photosynthesis	a	`and`
R_d	g C m^{-2}d^{-1}	rate of daily respiration of leaf	j	`rd`
	J m^{-2}d^{-1}	daily total absorbed PAR		`apar`
APAR	Mol photons m^{-2}d^{-1}	daily total absorbed PAR		
$C1_{C3}$	g C mol^{-1} photon	amount of carbon per mol photons	a	
	g C J^{-1}	amount of carbon per amount of energy		`c1`
$C2_{C3}$	(–)			`c2`
$C1_{C4}$	(–)	reducing factor on the optimal C_4 photosynthesis rate.		`c1`
$C2_{C4}$	(–)			`c2`
J_E	g C m^{-2}d^{-1}	response of photosynthesis to APAR under PAR limitation		
	g C m^{-2}h^{-1}			`je`
J_C	g C m^{-2}d^{-1}	Rubisco limited rate of photosynthesis		
	g C m^{-2}h^{-1}			`jc`
Φ_{TC3}	(–)	effect of low temperature on C_3 photosynthesis	a	`tstress`
T_c	(°C)	monthly temperature		`temp`
p_i	Pa	the intercellular CO_2 partial pressure	a, h, g	`pi`
p_a	Pa	partial CO_2 pressure	a	`co2`
Γ_*	kPa	CO_2 compensation point		`gammastar`
$[O_2]$	kPa	partial pressure of O_2		`po2`
V_m	g C m^{-2}d^{-1}	maximum daily rate of net photosynthesis	a	`vm`

In LPJmL code the daily gross photosynthesis is:

```
agd=(je+jc-sqrt((je+jc)*(je+jc)-4.0*theta*je*jc))/(2.0*theta)*daylength
```

With `b` (either `bc3` or `bc4`) and `vm` the amount of carbon in the daily respiration of leaf is calculated as:

rd=b*vm

The amount of carbon in the daily gross photosynthesis minus the daily respiration of leaf gives the parameter `and`.

$$And = \left(\frac{J_C + J_E - \sqrt{(J_C + J_E)^2 + 4\theta J_E J_C}}{2\theta} \right) - R_d$$

In LPJmL code: `and=agd-rd`

The parameter rd is the daily leaf respiration rate (g C $d^{-1}m^{-2}$) (Haxeltine & Prentice, 1996a). The daily respiration of leaf represents the CO_2 evolution from mitochondria in the light, other than that associated with the photorespiratory carbon oxidation cycle (Farquhar *et al.*, 1980). Some authors called this process dark respiration like Farquhar *et al.* (1980) however; the dark respiration is the respiration of the plant in darkness. In this report, the parameter rd is the daily respiration of leaf.

The previous part described the calculation of the gross and net carbon production in the next section the difference between those two, the total respiration, is discussed.

4.3.2 Respiration losses

The net primary carbon production (npp in LPJmL, g C $m^{-2}d^{-1}$) is derived from the gross primary carbon production (gpp or agd in LPJmL, g C $m^{-2}d^{-1}$) by subtracting the daily respiration of leaf (rd, g C $m^{-2}d^{-1}$) and respiration losses for maintenance of the plant and growth (Goudriaan & Van Laar, 1994; Haxeltine & Prentice, 1996a). The npp may be calculated by several methods. To be able to check the calculated respiration losses by LPJmL the results are compared with other respiration loss methods.

Method 1 (Haxeltine & Prentice, 1996a)
In LPJmL, the daily respiration of leaf (rd) is subtracted from the gross primary production to give the parameter `assim`.

```
assim = gpp - rd
```

`rd` = daily respiration of leaf (g C $m^{-2}d^{-1}$) (Eqn 10, Haxeltine & Prentice, 1996a). The daily respiration of leaf is related to maximum daily rate of net photosynthesis (`vm`) as:

```
rd = b*vm
b = bc3 or bc4
```

The parameter `b` (bc3 or bc4) is a fraction of `vm`. For C_3 plants bc3 = 0.0015 (–) and for C_4 plants bc4 = 0.02 (–) (Haxeltine & Prentice, 1996a).

In Figure 30 an example is given of the calculated gross and net production rates and in Figure 31 the net production and respiration rates of grassland for the Netherlands in 1987 and 1988 are given.

npp = assim – mresp – gresp (g C m^{-2} d^{-1}) [equation 1]
(net primary production = assim – maintenance respiration – growth respiration)

In LPJmL the maintenance respiration (mresp) of roots depends on the root mass, root specific C:N ratio, soil temperature, and plant phenology (Sitch *et al.*, 2003).

```
mresp = root mass*nind* (respcoeff*m /cn_ratio.root)*g(T)*phen
```

with:
`mresp` (g C $m^{-2}d^{-1}$)
`root mass` (g C m^{-2})
`nind` = 1 (plant m^{-2}, should be dimensionless)
`m` = 0.0548 (–)
`respcoeff C3` = 1.2 (g C g^{-1} N d^{-1}) Table 8
`respcoeff C4` = 0.2 (g C g^{-1} N d^{-1}) Table 8

`cn_ratio.root` = 29 (–) should be (g C g^{-1} N) Table 8, (Sitch *et al.*, 2003)
`phen` = phenology (–)

$$g(T) = e^{308.56 * \left(\frac{1}{56.02} - \frac{1}{T + 46.02} \right)} \quad (–) \qquad \text{(Sitch et al., 2003)}$$

`temp` = soil temperature, it depends on soil characteristics, the air temperature of previous days and a lag factor (°C)

308.56, 56.02 and 46.02 are temperatures in K (Lloyd & Taylor, 1994).

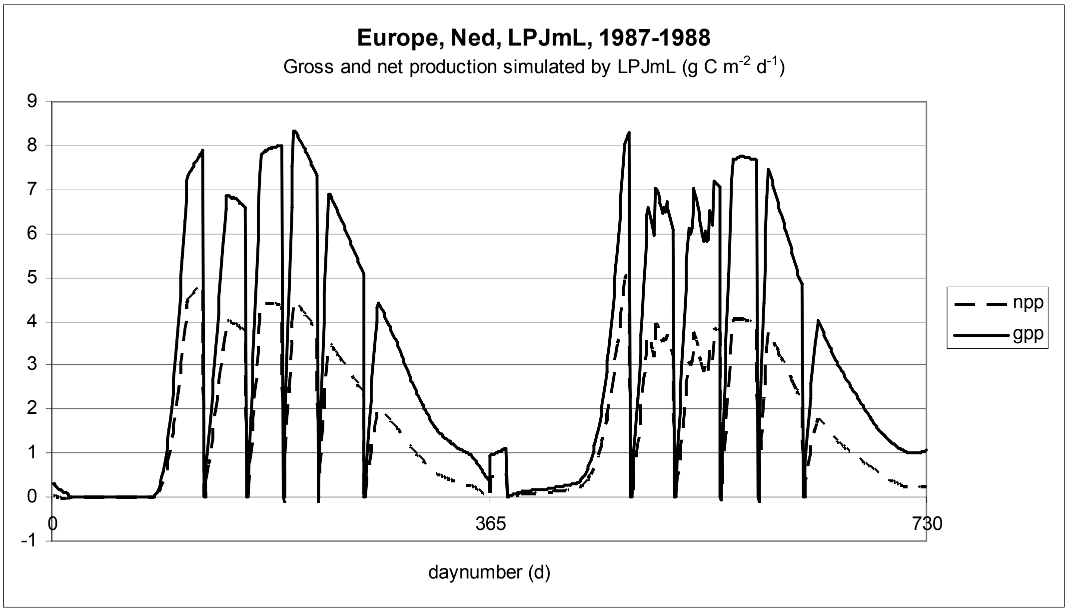


Figure 30 Gross and net production rates calculated by LPJmL for the Netherlands, 1987–1988.

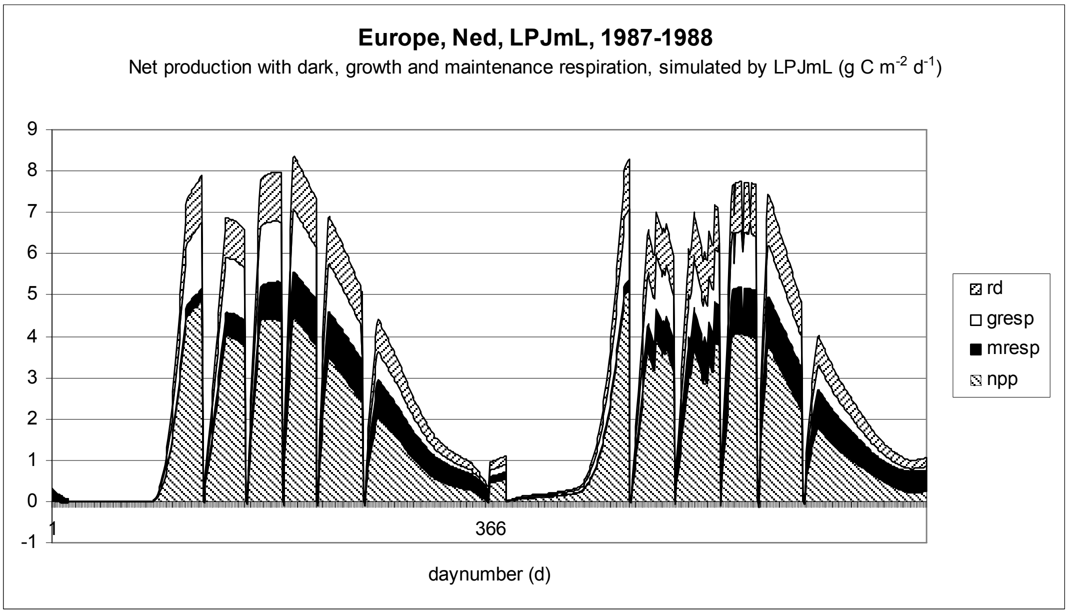


Figure 31 Net primary production, non-photorespiratory, growth and maintenance respiration rates calculated by LPJmL for the Netherlands, 1987–1988.

The equation of the temperature response ($g(T)$) is a modified Arrhenius equation (Lloyd & Taylor, 1994). In Figure 32 the value of the parameter `temp_response` is given for different temperatures (˚C) (Lloyd & Taylor, 1994).

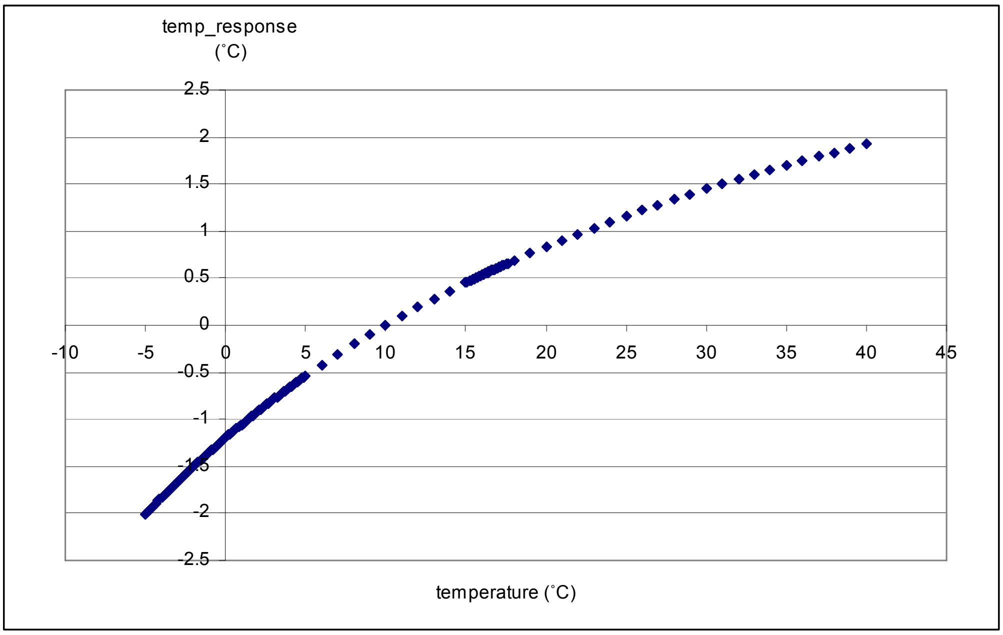


Figure 32 Value of parameter `temp_response` *with different soil temperatures (˚C) (Sitch et al., 2003 based on Lloyd & Taylor, 1994)*

In the LPJmL code the parameter `respcoeff` is multiplied with a parameter `k`. This is confusing because `k` is already used for the extinction coefficient. In this report the `k` with the `respcoeff` is replaced by an `m`.

The `respcoeff*m` is the PFT specific respiration rate (g C g^{-1} N d^{-1}) on a 10 ˚C base (Sitch *et al.*, 2003). In LPJmL, this is separated into m and a respiration coefficient to get a C_3 and C_4 specific maintenance respiration.

The growth respiration (`gresp`) is calculated as (gross primary production minus daily respiration of leaf minus the maintenance respiration times 0.25.

gresp = (gpp–rd–mresp)*0.25 (g C $m^{-2}d^{-1}$) [equation 2]

The calculation of the mresp in LPJmL is complex. To get an idea about the validity the mresp of LPJmL, it is compared with a more transparent method of Goudriaan & Van Laar (1994). Method 1 is the calculation of the npp according to LPJmL (described above), method 2 is the calculation of npp with LPJmL and only mresp from Goudriaan & Van Laar, method 3 is the npp and mresp calculated totally according to Goudriaan & Van Laar.

Method 3 (Goudriaan & Van Laar):
npp = (gpp – 0.03 * W) * CVF (g C $m^{-2}d^{-1}$)

W = weight of plant or crop (Goudriaan & Van Laar, 1994)
CVF = conversion factor (= 0.7) (Penning de Vries *et al.*, 1983).

npp_3 = (gpp – 0.03 * W) * (1–0.3)

npp_3 = (gpp – 0.03 * W) – 0.3 (gpp – 0.03 * W)   (g C $m^{-2}d^{-1}$)

mresp = 0.03 * W   (g C $m^{-2}d^{-1}$)
gresp = 0.3 (gpp – 0.03 * W)   (g C $m^{-2}d^{-1}$)

npp_3 = gpp – mresp – gresp
npp_3 = 0.7 * (gpp – 0.03 * W) (g C $m^{-2}d^{-1}$)

Method 2 (LPJmL with mresp from Goudriaan & Van Laar)
Gresp from Equation 2 filled in in gresp of Equation 1 leads to npp_2 :

npp_2 = gpp – rd – mresp – 0.25 * (gpp – rd – mresp)   (g C $m^{-2}d^{-1}$)

replace mresp with 0.03 *W from method 1:

npp_2 = gpp – rd – 0.03*W – 0.25 * (gpp – rd – 0.03*W)
npp_2 = gpp – rd – 0.03*W (1–0.25)
npp_2 = 0.75 * (gpp – rd – 0.03*W)   (g C $m^{-2}d^{-1}$)

npp_3= 0.7 * (gpp – 0.03 * W)   (g C $m^{-2}d^{-1}$)

Theoretical comparison of npp_2 with npp_3 shows just a small difference;
0.05 * gpp, 0.75 * rd and 0.0015 * W. Hence, the calculation of mresp by LPJmL is correct.

The calculation results of the npp per method are shown in Figure 33. The accumulation of npp gives the increment of carbon (`bm_inc`, g C m^{-2}) which will be the topic of the next section.

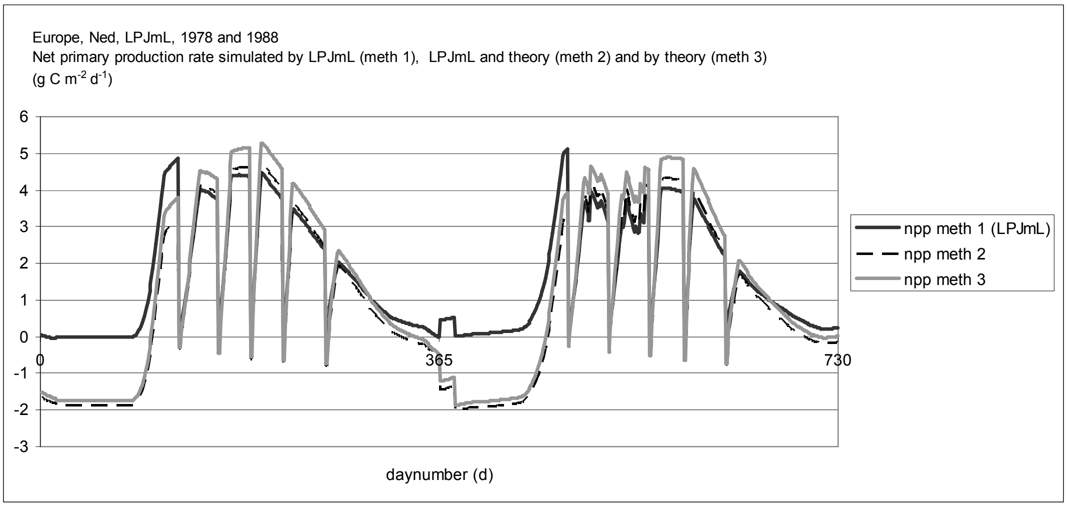


Figure 33 The npp calculated by LPJmL (method 1), calculation rules from LPJmL and the mresp from Goudriaan & Van Laar (method 2) and calculation according to Goudriaan & Van Laar (method 3).

4.3.3 Comparison of calculated accumulated biomass by LPJmL and LINGRA

To check the calculation of accumulated biomass by LPJmL, the results are compared with results from LINGRA (Bouman *et al.*, 1996, Schapendonk *et al.*, 1998). The grass growth model LINGRA is chosen because it is a well-documented, calibrated and validated model for European conditions. To be able to compare the dry matter production of LINGRA in kg per ha, the carbon production per m^2 of LPJmL is divided by 0.45 g C g^{-1} dm and multiplied by 10 (10000 m^2 ha^{-1} / 1000 g kg^{-1}). For three European locations the accumulated biomass calculated by LPJmL and LINGRA are compared for a period of five years. The Dutch location is Wageningen from 1970–1974 (Figure 34), Italian location is Bologna, 1982–1986 (Figure 35) and the Spanish location is Seville 1986–1990 (Figure 36). A final comparison for four years for a location in India is made although the validity of LINGRA is less sure for this region (Figure 38).

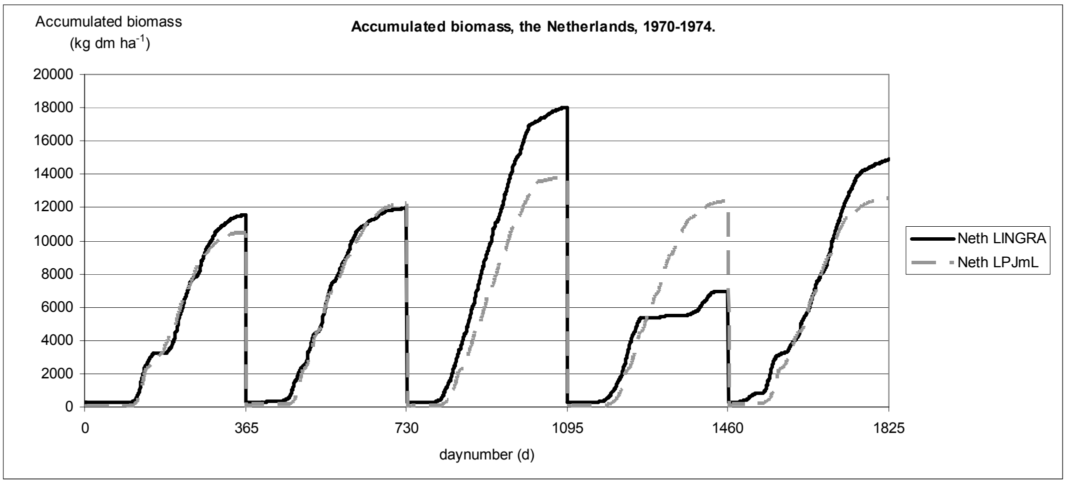


Figure 34 Accumulated biomass calculated by LPJmL and LINGRA for the Netherlands, Wageningen, 1970–1974.

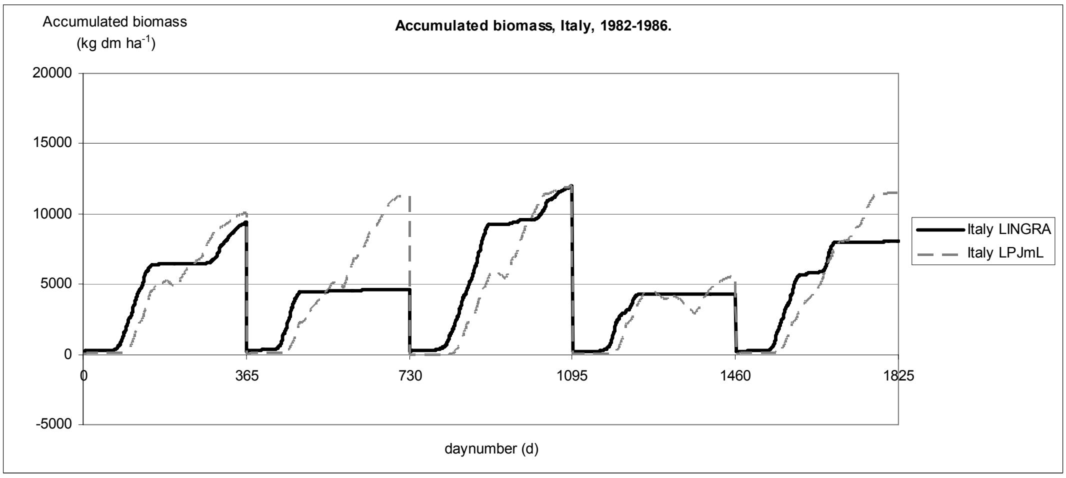


Figure 35 Accumulated biomass calculated by LPJmL and LINGRA for Italy, Bologna, 1982–1986.

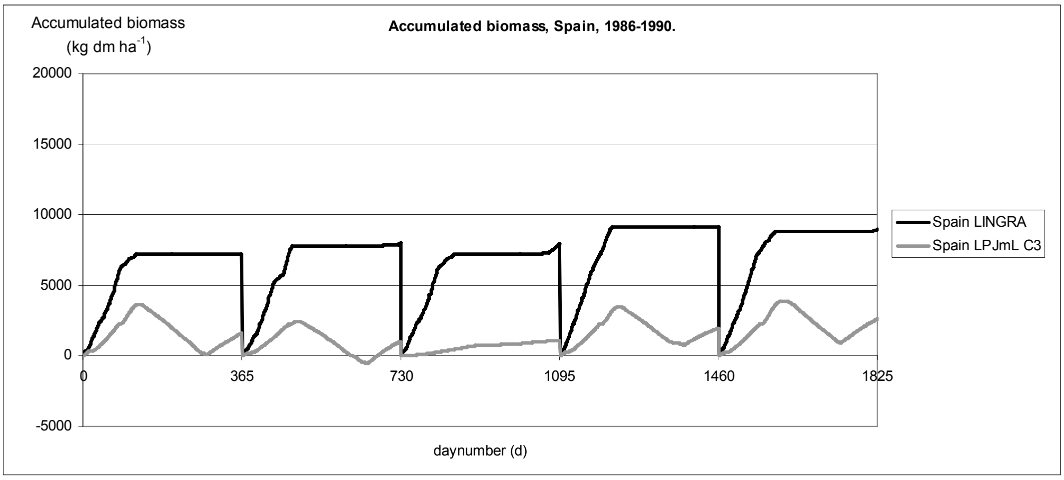


Figure 36 Accumulated biomass calculated by LPJmL and LINGRA for Spain, Seville, 1986–1990.

For the Netherlands the accumulated biomass of both models, coincide but LINGRA reaches higher maxima than LPJmL. For Italy, the accumulated biomass coincides well but sometimes LINGRA is lower. For Spain, LPJmL calculates a lower accumulated biomass than LINGRA. One of the reasons may be that LPJmL chooses a C3 grass (in Spain the `temp_min20` = 9 ˚C and LPJmL calculates with C3 when `temp_min20` < 15.5 ˚C, see 4.3.10).

When the settings in LPJmL are forced to C_4 grass the accumulated biomass of LPJmL is closer to the LINGRA accumulated biomass, but still underestimated (Figure 37, see also section 3.1.4). The onset of the biomass accumulation in LPJmL is slower than in LINGRA.

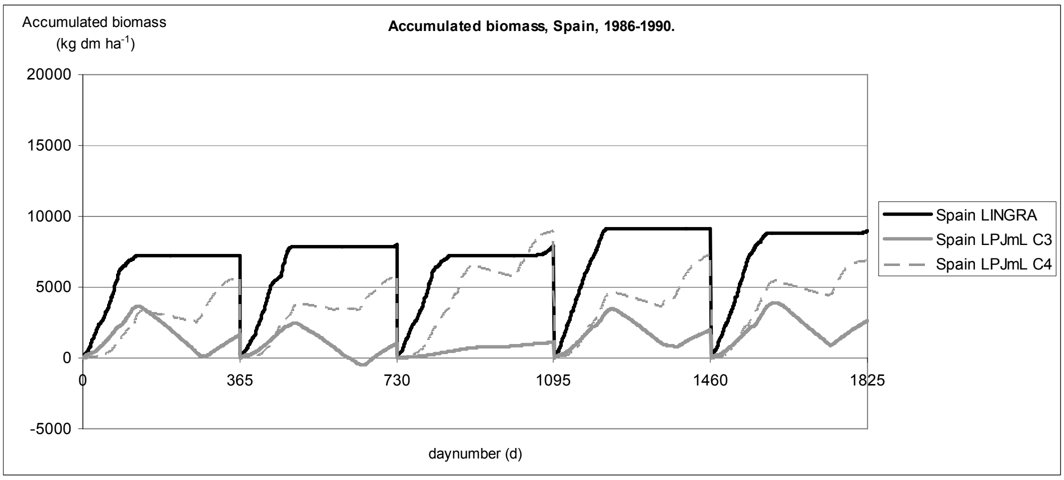


Figure 37 Accumulated biomass calculated by LPJmL with C_3 and forced C_4 settings and LINGRA for Spain, Seville, 1986–1990.

To check whether other locations with C_4 grasses are underestimated with LPJmL the accumulated biomass for a location in India is calculated with both models.

As Figure 38 shows, there is no underestimation of the maximum accumulated biomass of a C_4 grass, calculated with LPJmL for the location Patancheru in India for 1978–1981. There is another difference: LINGRA starts with some biomass production at the beginning of the year but the growth stops due to dry circumstances. Apparently, there was enough water to start the production. For LPJmL there was not enough water to start the production and after the dry period, LPJmL started the biomass production a little earlier than LINGRA and both models end up with the same accumulated biomass curve for three out of four years.

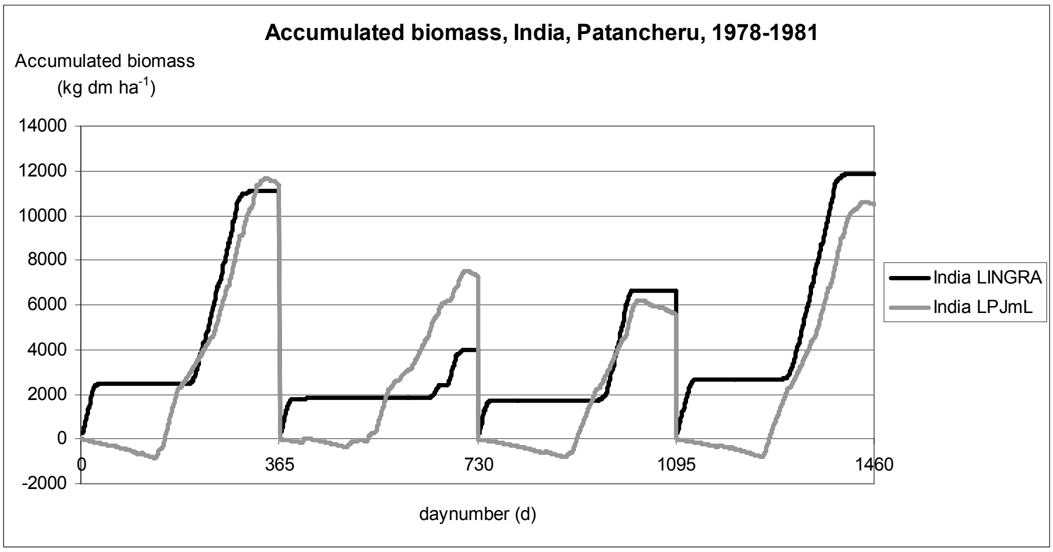


Figure 38 Accumulated biomass calculated with LPJmL and LINGRA for India, Patancheru, 1978 – 1981.

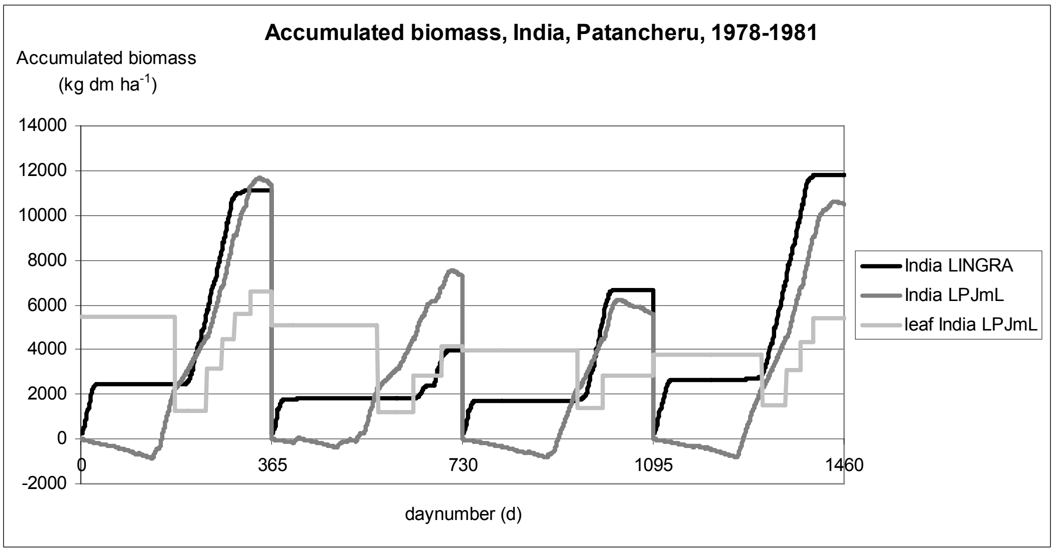


Figure 39 Accumulated biomass calculated with LPJmL and LINGRA and amount of leaf for India, Patancheru, 1978–1981.

The accumulated biomass calculated by LPJmL seems to get a negative value at the beginning of the year because of respiration losses. At the end of the previous year, LPJmL calculates an amount of biomass that is left in the leaves for next year (Figure 39, see also 4.3.5.4). This amount acts as a reserve for biomass until the first harvest (for example day 181 for 1978). For India, the amount of biomass in the leaves exceeds the negative biomass accumulation.

4.3.4 Phenology

Phenology is the study of periodic plant life cycle events and the influence of seasonal and inter-annual variations in climate on this cycle (Wikipedia). Because of its importance of influencing the development of crops, the phenology is implemented in LPJmL.

In LPJmL, the calculation of the phenology of grass starts with the calculation of the parameter `dtemp`, which is the temperature (`temp`) minus the base temperature (`gddbase`).

```
dtemp  = temp - gddbase, if dtemp>0, else dtemp=0
gdd    = gdd + dtemp
phen   = gdd * ramp
```

with:

`dtemp` = the temperature minus the base temperature (˚C)
`gddbase` = the base temperature (˚C): below this temperature there is no grass growth for C3 and C4 this temperature is set to 5.0˚C (Table 8)
`gdd` = growing degree days (˚C) temperature sum
`phen` = phenology
`ramp` = number of gdd's to attain full leaf cover (set to 100 and changed in de calculation process to 0.01 for C3 and C4 grasses, seeTable 8).

Below the base temperature, there is no grass growth. The base temperature is the same for C_3 and C_4 grasses and set to 5 ˚C (Table 8). The growing degree-day (`gdd`) is the accumulated `dtemp` or temperature sum. To get the value of parameter `phen` (phenology) the temperature sum is multiplied with the number of `gdd` to attain full leaf cover (`ramp`,Table 8). The value of `ramp` is 100 but is converted (strange enough and confusing) to 0.01 during the calculation run.

Calculated like this and according to the unit (˚C) the parameter `phen` in LPJmL is rather a temperature sum than the development state of the grass (as it suggests). In LPJmL, the phenology of grass is calculated on a daily basis and has a value between zero and one. If the calculated phenology gets higher than one the phenology is set to one. It is not known what the state of the grass is when the value of `phen` is zero or one.

The value of the `phen` is set back to zero when the next harvest moment or the coldest day of the hemisphere the grid belongs to is reached (Figure 40).

There is no difference between the calculated phenology of C_3 or C_4 grasses, because the calculated `gdd`, `ramp` and base temperature are the same (see also section 6.3).

The parameter `phen` plays and important role in LPJmL because it is part of a lot of processes such as the calculation of *LAI*, the fraction of incoming *PAR* intercepted by green vegetation (*FPAR*), water supply (water availability) and demand, maintenance respiration and the phenology is one of the two deciding parameters for a harvest moment.

Table 8 Parameter values of C_3 and C_4 grasses.

Parameter name	**Des-cription**	**Par nr**	**C_3 perennial grass**	**C_4 perennial grass**	**Source**
pft			8	9	
rootdist[0]		1	0.80	0.80	
Minwscal		3	0.20	0.20	
gmin		4	0.5	0.5	1
respcoeff		5	1.2	0.2	
nmax		7	100	100	
resist	1	8	0.01	0.01	
sla (= longivity)		10	0.5	0.5	
lmro_ratio		18	0.75	0.75	1
ramp		19	100	100	2
lai_sapl		21	0.001	0.001	
gdd5min		30	0	0	
twmax		31	1000	1000	
gddbase (ºC)		33	5.0	5.0	4
min_temprange		34	–1000	–1000	
emax		35	5.0	7.0	
intc		36	0.01	0.01	
alphaa	2		0.5	0.5	
phenology			ANY	ANY	
pathway			C3	C4	
lower and upper temperature limit for photosynthesis (ºC)		24 27	–4.0 45.0	6.0 55.0	
lower and upper limit of optimum temperature for photosynthesis (ºC)		25 26	10 30	20 45	
lower and upper coldest monthly mean temperature (ºC)		28 29	–1000 15.5	15.5 1000.0	15.5 from 4
turnover leaf root		9 12	1.0 2.0	1.0 2.0	3
C:N	3	13 15	CTON_LEAF(=29) CTON_ROOT(=29)	CTON_LEAF (=29) CTON_ROOT (=29)	4

Source 1 Gerten *et al.*, 2004
Source 2 Sitch *et al.*, 2003*
Source 3 Sitch *et al.*, 2003**
Source 4 Sitch *et al.*, 2003

* when used in LPJmL -> 0.01 see also Conclusions about the code
** when used in LPJmL -> 0.5
Description 1 fire resistance index
Description 2 fraction of PAR assimilated at ecosystem level, relative to leaf level
Description 3 mass ratio for leaf and root
The value ANY means that the value of this parameter is calculated.

4.3.5 Harvest

In LPJmL, there is no difference between mowing and grazing of grass, all removal of (part of) the vegetation is called harvest. There are several important issues concerning the harvest of grass:

- moment of harvest (when)
- harvest level (how much is harvested)
- procedures at harvest moment

- calculation of allocation ratio
- allocation of incremented biomass to root and leaf
- reset of incremented biomass and phenology to zero

4.3.5.1 Harvest moment

The moment of harvests in LPJmL is determined by

- a threshold value of the incremented (or accumulated) carbon and
- a threshold value of the parameter phenology.

The amount of carbon produced by the photosynthesis is calculated on a daily basis. The integral amount of produced carbon between harvests is called incremented biomass in the LPJmL code. This amount of accumulated biomass is one of the two deciding parameter for a harvest moment. The value of the phenology is the other deciding parameter.

The default threshold of accumulated biomass for a harvest moment is set to 100 g C m^{-2} in LPJmL. This is about 2000 kg dm ha^{-1} and a reasonable harvest (under grazing) for temperate conditions in the Netherlands. For mowing, the level should be at 135 g C m^{-2} or 3000 kg dm ha^{-1} (see 6.7.1).

The default value of the phenology for a harvest moment of grass is one. Both threshold values are fixed values in the LPJmL code. At a harvest moment the allocation of incremented biomass to leaf, root, harvest (leaves only) and litter (leaves and roots) is calculated, so the allocation is not calculated on a daily basis. After the allocation of the accumulated biomass the value of the accumulated biomass and the phenology are set to zero. The phenology is not reset to zero at the end of the year but on the coldest day (see 4.3.5.5).

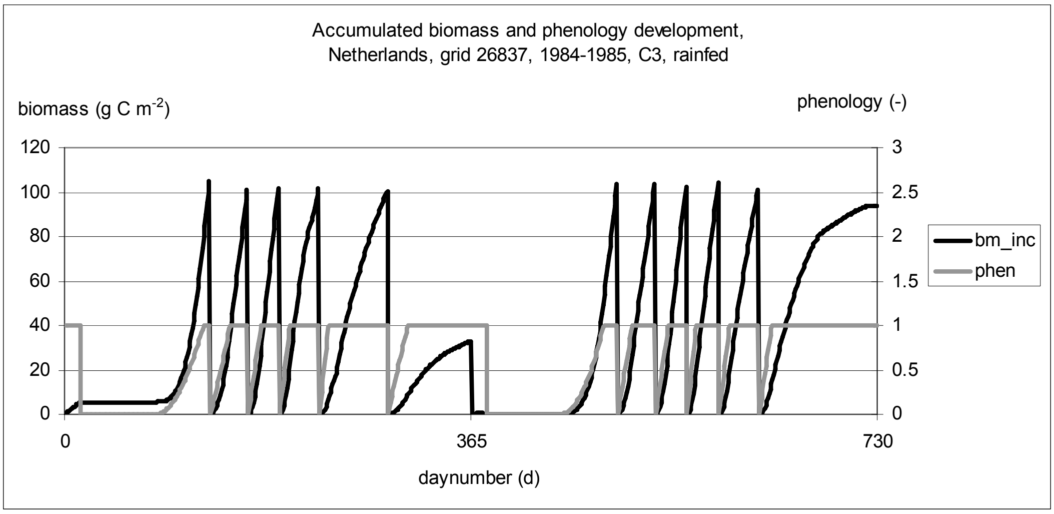


Figure 40 The increment of biomass and phenology of grass in the Netherlands for 1984 and 1985. Harvests occur when incremented biomass is 100 g C m^{-2} and phenology is one.

In Figure 40 an example of harvest moments for 1984 and 1985 in the Netherlands is given. The threshold values of biomass increment of 100 g C m^{-2} and phenology one (–) and the reset of the accumulated biomass and phenology to zero are obvious. The threshold value of incremented biomass can be changed. A low threshold mimics a higher grazing or mowing frequency (`phenology_grass.c`). When the mow or grazing frequency increases, a decrease in production may be expected because the grass has no time to restore and reserves are exhausted. If the harvest frequency decreases, the production may decrease as well because of increase in shading.

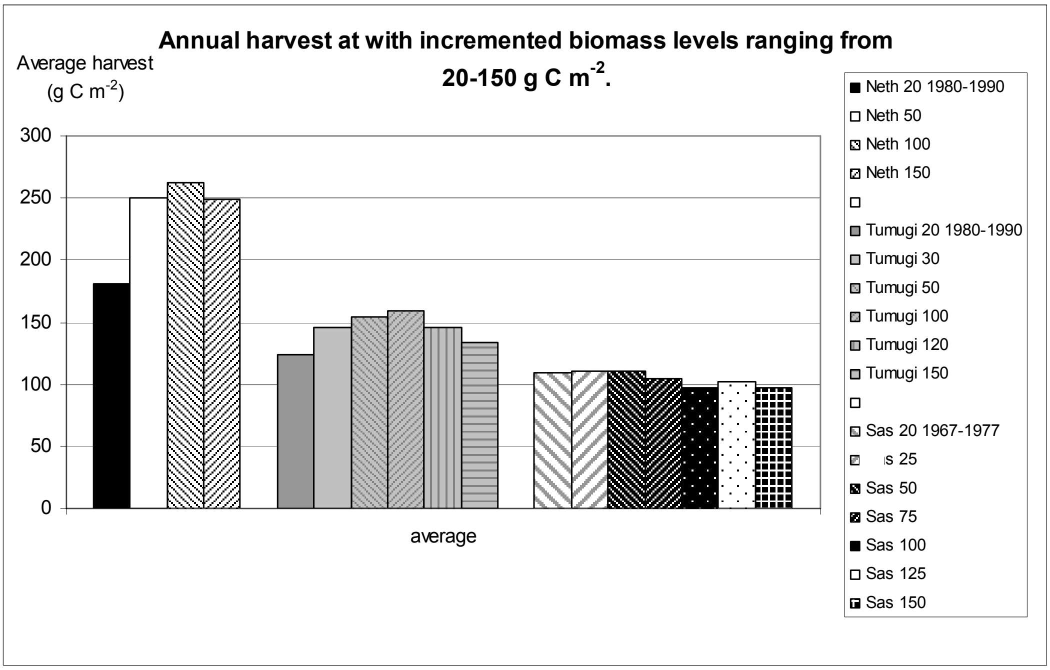


Figure 41 Effect on harvest when changing the harvest threshold from the default value 100 g C m^{-2} to higher and lower levels for the Netherlands, China (Tumugi) and Canada (Saskatchewan).

In Figure 41, the effect of changing the threshold from the default value of incremented biomass of 100 g C m^{-2} to 20 – 150 g C m^{-2} is given.

In the Netherlands and Tumugi, a deviation from 100 g C m^{-2} results in a decrease of harvest as expected. LPJmL seems to be more sensitive for a deviation from the 100 g C m^{-2} value for the Netherlands than for China. In Dutch practice, the harvest may take place in a range from 100 – 200 g C m^{-2} without production losses. Between 100 and 150 g C m^{-2} this is simulated by LPJmL as well. In Canada, a slight increase occurs when the threshold is lowered from 100 to 25 g C m^{-2}.
The threshold value of the phenology may be altered as well but because this parameter is used in several places in the code this may have unwanted side effects (see 4.3.4).

4.3.5.2 Harvest level

The harvest level, how much of standing grass is harvested, is a fixed value in the LPJmL code of the `litter_update_grass` function. This fraction (parameter `frac`) is set to 0.5 as indicated in the `litter_update function` in `harvest_stand.c`.

File `Litter_update_grass.c`

```
Harvest litter_update_grass(litter, pft, frac, isharvest)
```

File `Harvest_stand.c`

```
harvest = litter_update(litter,pft,0.5,TRUE)
```

with:

`litter` = litter pool
`pft` = PFT variables
`frac` = fraction (0..1)
`isharvest` = is there a harvest (TRUE/FALSE)

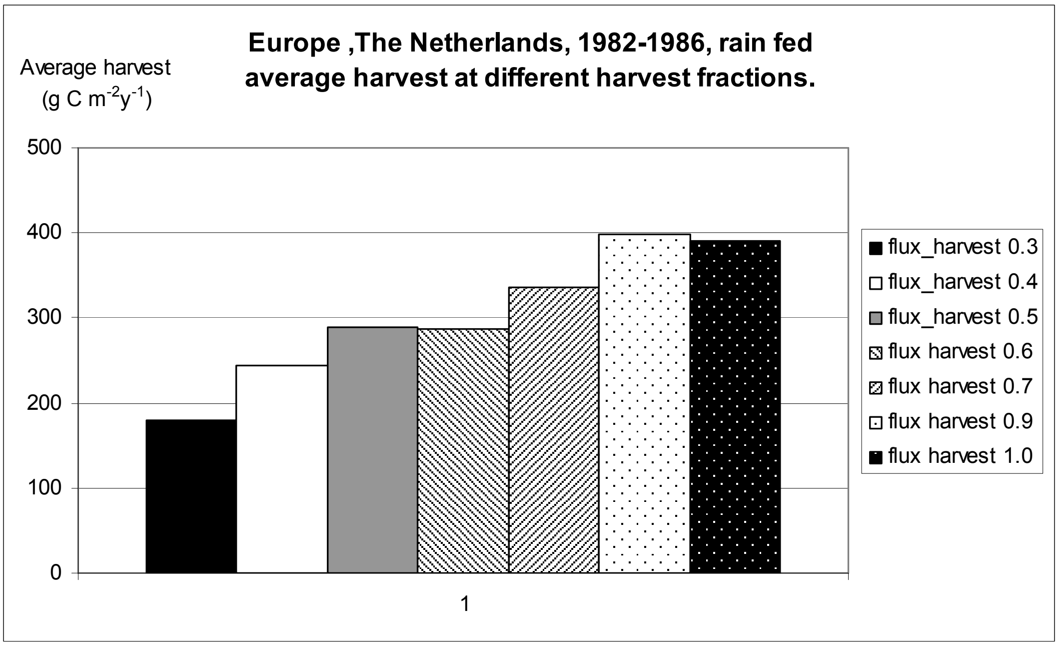


Figure 42 Effect of altered harvest fraction from default value 0.5 on amount of carbon harvested per year for one grid in the Netherlands (average of 1982–1986).

This level is the same for all grasslands in all grids and means that half of the leaf material is harvested (or grazed). Grassland investigations in the Netherlands, the UK and South Africa (Scholes, 1998) use a grazing height of 5 cm (about 10% of aboveground material). A stubble of 5 cm of aboveground matter contains 200 – 400 kg dm ha^{-1}. In France, a minimum value of available grass for dairy cows of 800 kg dm ha^{-1} is used (Cros *et al.*, 2003). This means that more grass is harvested than the 50% harvest used in LPJmL however, for natural grasslands the harvest level will be lower and less uniform.

If the harvest fraction in LPJmL is altered, all the grasslands will be harvested at that level. If the level is higher, more grass is harvested and less plant material is left for regrowth. This should lead to a decrease in harvested material with rising harvest fraction. In Figure 42 an example for the Netherlands is given. The harvest (production) decrease happens only at the end of the scale (harvest 1.0) when almost all leaf biomass is harvested, this is later than expected.

4.3.5.3 Allocation ratio

The allocation ratio is the determining parameter for the distribution of the amount of accumulated biomass (g C m^{-2}) to root and shoot. This allocation ratio depends on a fixed root/shoot ratio (0.75, Sitch *et al.*, 2003; Table 3) and the transpiration as described in detail in Gerten *et al.* (2004). The transpiration is modeled as the lesser of an atmosphere-controlled water demand function and a plant-controlled water supply function (Federer, 1982).

Water supply

The parameter supply is determined by the maximum transpiration rate that can be sustained under well-watered conditions (`emax`, mm d^{-1}) and declines linearly with relative soil moisture (`wr`) (Gerten *et al.*, 2004). As an addition to the formula of Gerten the supply of LPJmL depends on the phenology as well.

```
supply = emax*wr*phen
```

The maximum transpiration is 5.0 (mm d^{-1}) for a C_3 grasses (Kelliher *et al.*, 1993) and 7.0 (mm d^{-1}) for a C_4 grass. The relative soil moisture is the amount of water in the soil layers between harvests and depends on the current soil water content and plant-available water capacity (`whc`, the texture-dependent difference between field capacity and wilting point). In LPJmL, the soil consists of two layers each with a fixed thickness: upper layer 0.5 m and lower layer of 1.0 m. The rooting depth for grass is 0.8 m.

The soil evaporates from a different soil depth, the upper 0.2 m. The relative soil moisture (`wr`) is calculated for both soil layers by weighting their relative soil water contents with the fraction of roots present in the respective layer.

The water supply per PFT is calculated as

```
supply_pft=emax*wr*phen*FPC
```

With *FPC* = foliage projective cover (see Annex 2)

Water demand

The atmospheric demand represents unstressed transpiration (Federer, 1982) which occurs when the opening of the stomata is not limited by reduced water potential in the plant. Following Monteith (1995) daily demand is a hyperbolic function of canopy conductance (the sum of stomatal conductance of all leaves for a given PFT):

```
demand = (1.0-wet)*pet*ALPHAM/(1+GM/gp_stand)
```

Where

`wet` is the fraction of day-time that the canopy is wet (–)

`pet` is the daily equilibrium evapotranspiration rate (mm/d) (Gerten *et al.*, 2004).

`ALPHAM` = 1.391 a maximum Priesley-Taylor coefficient (–) (Huntingford & Monteith, 1998)

`GM` = 3.26 a scaling conductance mm s^{-1} (Huntingford & Monteith, 1998)

`gp_stand` is the potential canopy conductance that can be achieved when there is no water limitation (mm s^{-1}).

The `demand` approximates `pet*ALPHAM` when the canopy is dry and `gp_stand` tends to infinity. The parameter `gp_stand` or `gp_pft` is directly related to the photosynthesis rate as follows (details in Haxeltine and Prentice, 1996a and Sitch *et al.*, 2003).

```
gp   =(1.6*npp/(ppm2bar(co2)*(1.0-
     lambda_opt)*hour2sec(daylength)))+gmin*FPC                  (mm s-1)
```

`gp_pft = gp*phen` (per plant functial type)

`gp_stand+ = gp*phen` (per grid)

`npp` = daytime net photosynthesis rate (g C $m^{-2}d^{-1}$).

`ppm2bar(co2)` = ambient CO_2 (mole fraction)

`lambda_opt` = the stomata-controlled ratio between intercellular and ambient CO_2 partial pressure in the absence of water limitation; it is lower for warm-zone C_4 grasses (0.4) than for C_3 grasses (0.8).

In LPJmL, there is only one value for `lambda_opt`, 0.8 (`gp_sum.c`).

The parameter `gmin` is the PFT specific minimum canopy conductance that accounts for plant water loss not directly linked to photosynthesis (e.g. guttation). For C_3 and C_4 grasses, the value of `gmin` is 0.5 in LPJmL (Gerten *et al.*, 2004).

After this explanation of water supply and demand we return to the first topic of this section, the allocation of assimilates to root and shoot. The allocation depends on the fixed allocation parameter `lmro_ratio` (0.75) and parameter `wscal_mean`:

```
wscal  = (emax*wr)/(pet*ALPHAM/(1+GM/gp_stand_leafon)) or supply/demand
lmtorm = lmro_ratio*(wscal_mean/365)
```

with:

`wscal_mean` = the accumulation of wscal between harvests.

In a drier period, when the `supply` is lower, the `wscal` is lower, the `lmtorm` is lower and more biomass will allocate to the roots. When more than enough water is available the plant can use assimilates to produce leaves rather than roots.

In Figure 43 the allocation ratio for a wet and dry year in the Netherlands is given. In the dry year (1976), the value of parameter `lmtorm` is lower, and more biomass goes to the roots (according to the calculation rules of next section).

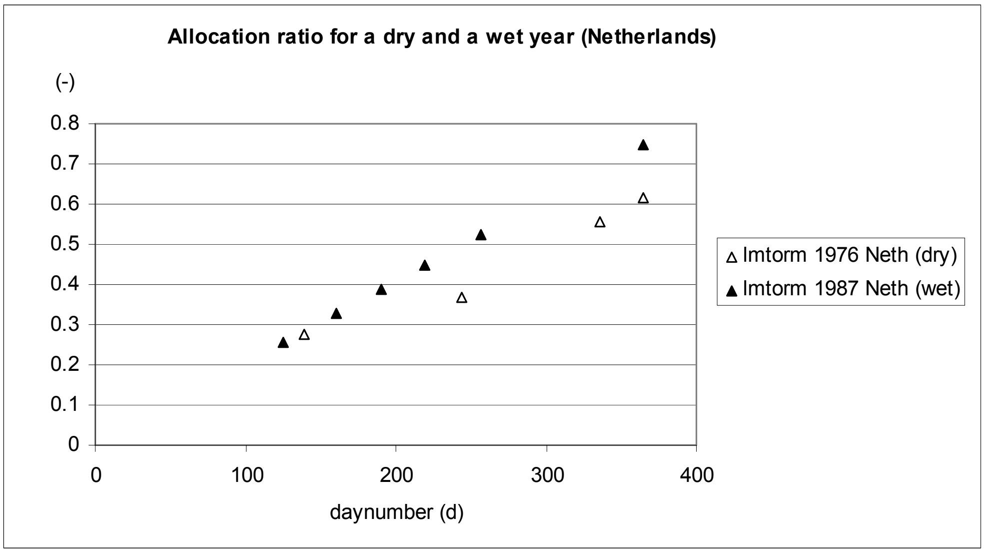


Figure 43 Calculated allocation parameter (lmtorm) by LPJmL for a dry (1976) and a wet (1987) year, the Netherlands.

4.3.5.4 Allocation of accumulated biomass to root and leaf

In the previous subsection, the value of the allocation variable `lmtorm` is calculated. The decision whether newly formed biomass is allocated to the leaves or the roots is based on this value. If the allocation parameter is very small (`lmtorm`<1.0e–10) all newly formed biomass, since the last harvest, allocates to the roots. Otherwise, the amount of carbon that will go to the leaves is calculated according to the equation of the calculation of i_leaf.

$$i\_leaf = \frac{biomass + root - (leaf / lmtorm)}{(1.0 + 1.0 / lmtorm)} \qquad (\text{g C m}^{-2})$$

leaf	= the current amount of carbon in the leaves (before harvest)
root	= the current amount of carbon in the roots (before harvest)
biomass	= accumulated amount of carbon in biomass after the last harvest (or last day of the previous year)

i_leaf = interim parameter, amount of carbon from accumulated biomass, due to be added to the current amount of carbon in leaf

lmtorm = allocation parameter (–)

The value of i_leaf may be positive or negative. The physiological meaning of a positive i_leaf is that there are enough roots to sustain the amount of leaves and relative more carbon is allocated to the leaves than the roots (leaf and root growth). The pysiologial meaning of a negative i_leaf is that there are not enough roots to support the leaves and more carbon is allocated to the roots and the amount of leaves is reduced (often the first harvest of the year has a negative i_leaf).

First, a negative i_leaf is considered (moment A in Figure 44). When the i_leaf is negative, all newly formed accumulated biomass from the beginning of the year is allocated to the roots and the (negative) amount of carbon taken from the leaves is calculated as:

n_leaf = (root+biomass)*lmtorm – leaf

Because the threshold of accumulated biomass is 100 g C m^{-2} the amount of carbon to the roots is 100 g C. The physiological meaning of allocations of accumulated biomass to the roots is growth and reserve building in the roots.

The amount of n_leaf is allocated to leaf litter (meaning dying of grass leaves).

The amount of carbon in the leaves decreases (moment A Figure 44) because

$leaf_{(t+1)} = leaf_{(t)} – n\_leaf$

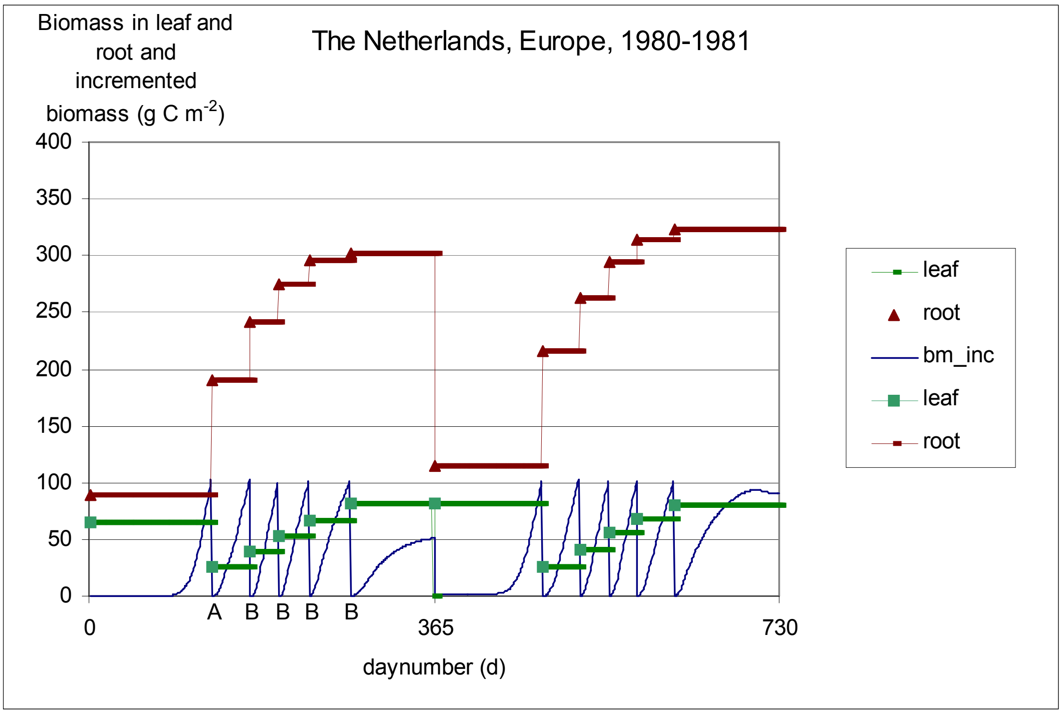


Figure 44 Incremented biomass (bm_inc) and allocation of incremented biomass to leaf and root at different harvest moments.

When the value of the allocation parameter (i_leaf) is positive this amount is added to the existing amount of carbon in the leaves (leaf growth). The amount of carbon that goes to

$leaf_{(t+1)} = leaf_{(t)} + i\_leaf$

the leaves (i_leaf) is subtracted from the carbon in incremented biomass, the remainder goes to the roots (i_root) (all B moments Figure 44) (root growth).

i_root = biomass – i_leaf

The carbon allocated to leaf and root (i_leaf and i_root) is added to the existing/former amount of carbon in leaf and root (see Figure 53).

The total amount of carbon in the leaf after harvest is:

$leaf_{(t+1)}$ (after harvest) = $leaf_{(t)}$ (before harvest) + i_leaf
$root_{(t+1)}$ (after harvest) = $root_{(t)}$ (before harvest) + i_root

After calculation of the amount of carbon in the leaves next step in the harvest procedure is: half of the amount of carbon in the leaves goes to harvest and the other half remains in the leaf.

With the newly formed amount of carbon in the leaves, the *FPC* is recalculated (section 4.3.7). These calculations occur on one specific day, the harvest day or moment (see Figure 48).

At the end of the year, on day 365 (e.g. 170 g C m^{-2} in the leaves and 350 g C m^{-2} in the roots), half of the carbon in leaves goes to harvest (85 g C m^{-2}) and half to leaf litter (85 g C m^{-2}). So one moment, on day 365, the amount of carbon in the leaves is zero. Half of the carbon in root goes to root litter (e.g. 175 g C m^{-2}), and part of it goes to the leaves. If any biomass is formed between the last harvest and day 365 (e.g. 40 g C m^{-2}), 10% of this biomass is subtracted as reproduction losses (4 g C m^{-2}) (Sitch *et al.*, 2003) and added to leaf litter. However, that should rather go the atmosphere in the form of respiration losses. The remainder (90%, 36 g C m^{-2}) of this latest produced carbon goes to carbon in the leaves.

The parameter i_leaf (amount of carbon to leaf) is calculated again with the reduced amount of incremented biomass and no carbon in the leaves and half of the carbon of the roots. When the value of `lmtorm` is 0.68 in the example this will give:

$$i\_leaf = \frac{36 + 175 - (0/0.68)}{(1.0 + 1.0/0.68)} = 85.4 \text{ g C m}^{-2}$$

This value of i_leaf (85.4 g C m^{-2}) is supplied with the incremented biomass (36 g C m^{-2}) and carbon from the roots if the incremented biomass is not sufficient (85.4–36 = 49.4 g C m^{-2}). The remainder of the amount of carbon in the roots is 175 – 49.4 = 125.6 g C m^{-2}. This explains the drop of carbon amount in the root at day 365 and the increase of biomass in leaf on day 1 (Figure 44). Plant physiologically this means that the reserves in the root are used for leaf growth on day one, which is a strange moment both on the northern and southern hemisphere (but computationally necessary to get a value for carbon in the leaves until the next harvest moment).

In 4.3.5.6 a flow chart of the harvest procedure is given and the carbon flows per day, on a harvest day and for one year are shown in Figure 51 and Figure 54, section 4.4.

4.3.5.5 Combined effect of incremented biomass and phenology

After allocation of the incremented biomass to roots, leaves and/or litter the amount of the incremented biomass between harvests and the phenology are set back to zero. This way of calculating growth is possible, because the development of leaf area index, and thus light interception, is driven by a temperature sum only and a fixed value of specific leaf area and not by leaf weight per square meter of soil and a corresponding specific leaf area. However, the combined effect of accumulated biomass and phenology needs additional investigation.

The amount of carbon in incremented biomass is set to zero:
- during a harvest moment;
- at the end of the year (kind of harvest event).

The phenology is set to zero:
- on a harvest day;
- on the coldest day of the year.

When the value of phenology is set to zero, `FPAR` becomes zero (see 4.2.3), `APAR` becomes zero (see 4.2.2) and no biomass is produced. The value of incremented biomass stays steady during the period that the value of phenology is zero. If the period that the phenology is zero crosses the year boundary and the amount of carbon of the incremented biomass is not zero, the amount of incremented biomass is set to zero on the last day of the year.

On the coldest day of the year, the temperature sum (`gdd`) and phenological are set to zero. The coldest day on the northern hemisphere is on the 14th Julian day and the coldest day on the southern hemisphere is set on day 195 of the Julian calendar.

The implication of phenology and biomass reset to zero for a location on the southern hemisphere in South America is given (Figure 45).

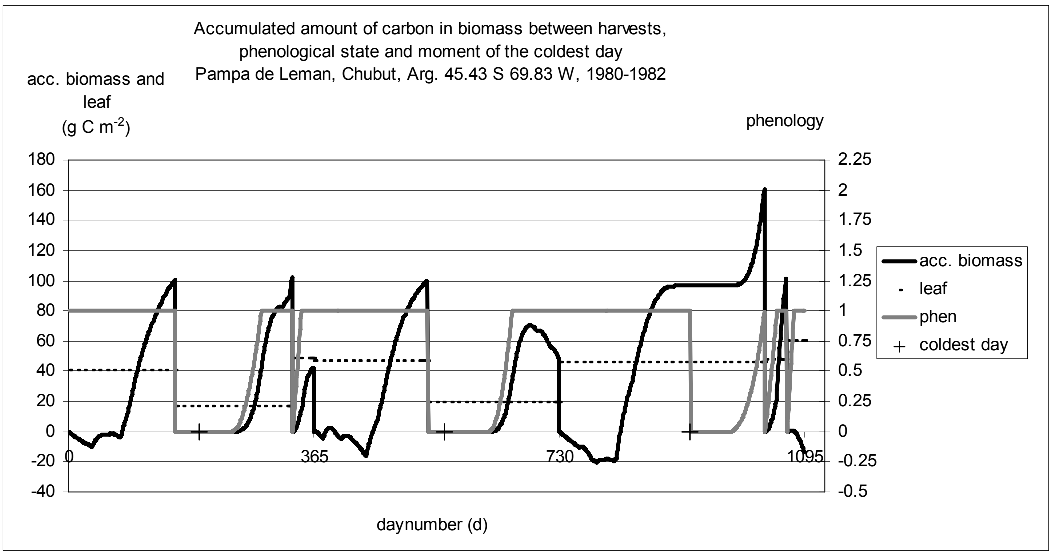


Figure 45 The amount of carbon in accumulated biomass and leaf (g C m^{-2}), the phenology of the grass and the coldest day in South America for 1980 to 1982.

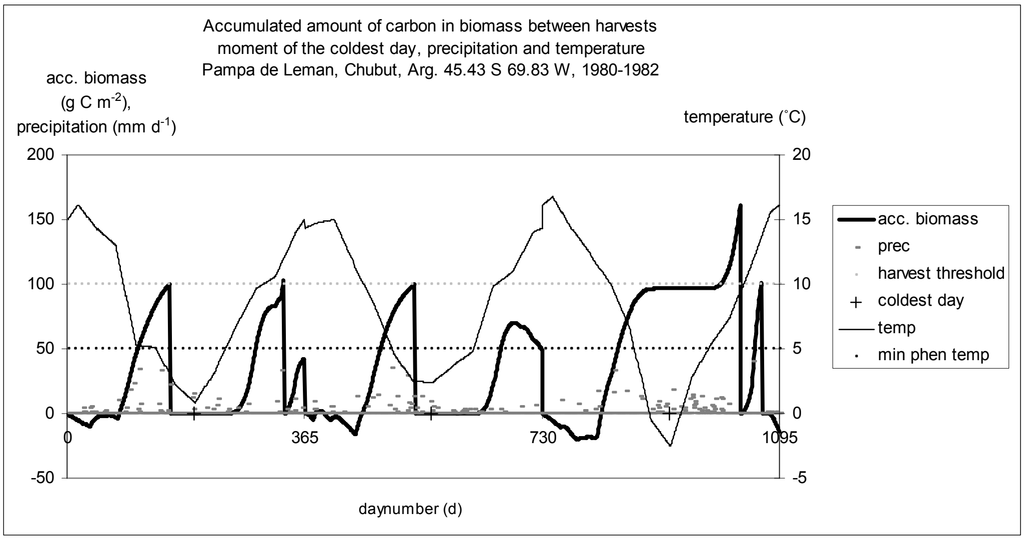


Figure 46 The amount of carbon in total accumulated biomass, temperature, precipitation, coldest day, temperature threshold for phenology (min phen temp) and biomass threshold for harvest of South America for 1980 to 1982.

In this example we follow the biomass and phenology of Pampa de Leman from 1980–1982. In 1979, a harvest took place and apparently, the temperature was high enough to result in phenology 1 on day one of 1980 and an amount of carbon in the leaves. The amount of incremented biomass is set to zero on day 365 of year 1979. With the phenology larger than zero, carbon production is not prohibited by phenology or temperature, but water stress decreases the amount of biomass below zero from day one of 1980. A decrease of incremented biomass is possible because there is also carbon in the leaves and roots that act as a reserve (only carbon in leaves is shown in Figure 45). After precipitation (Figure 46), the amount of carbon in accumulated biomass starts to increase on day 84. On day 158, the incremented biomass reaches 100 g C m^{-2} and because the phenology is still one, a harvest takes place. In Figure 46 the increment of biomass, the precipitation (mm d^{-1}), the harvest threshold, the coldest day of the year, the temperature and the base temperature of the phenology (5 °C) are given. At day 243 (1980) when the temperature rises above the base temperature of 5 °C the value of the phenology increases again (Figure 45 and Figure 46) and accumulation of carbon in biomass follows the phenology (Figure 45).

Next harvest occurs at day 334 in 1980 (Figure 45 and Figure 46). Because the temperature is above 5 °C, the phenology and biomass increases after day 334. At day 365 (the end of the year) the model forces a 'harvest' and the biomass is set to zero but the value of the phenology stays at one.

From day one of 1981 the circumstances are to dry for biomass growth until day 444. The phenology is still one and biomass accumulates until 100 g C m^{-2}. At day 535, the harvest takes place. The temperature is below the phenology threshold of 5°C and there is no biomass production. This continues until day 638 when the temperature rises above the 5°C threshold, phenology starts to rise until is reaches the value one at day 665. The biomass production followed the onset of phenology increment. At day 689, the biomass starts to decrease because of drought. At day 730 it is the end of the year 1981 and the amount of accumulated biomass is set to zero, the phenology stays at one. After day 815, the amount of biomass starts to increase and it reaches a value of 96.8 g C m^{-2}, at day 925, the coldest day is reached and the phenology turns to zero. Because the temperature is below the phenology incremental threshold, the phenology stays zero until day 989 when it starts to rise until it reaches the value of one on day 1035. This event causes a harvest because the biomass has crossed the threshold of 100 g C/m^2 already. Because of high temperature and precipitation, a second harvest follows at day 1068, 33 days later.

The artificial reduction of accumulated biomass at the end of the year may be plausible for locations at the northern hemisphere, but at this location in South America, it has an unwanted side effect. There is no environmental need for zero biomass growth at the end of the year, the temperature is above 5°C and the precipitation is high enough. Assumption of a reset of the biomass to zero only after a harvest and not at the end of the year gives the following results (Figure 47). The start of this experiment is at the end of year 1980: the accumulated biomass reached a value of 42 g C m^{-2} at day 365, if the growth continues, harvest conditions are met at day 486 (day 121 in 1981). This is 48 days earlier than with the set back of biomass to zero at day 365.

This would mean an earlier harvest to the farmer with probably a higher quality grass. The same happens at the end of 1981. The increment of biomass is set to zero and the threshold of 100 g C m^{-2} biomass is reached at the end of the 1982. Without the set back of biomass, harvest conditions are met at day 848 (day 118 of year 1982) instead of day 1035 (day 305 of year 1982). This characteristic of LPJmL could lead to underestimation of harvested grass and mismatch of the timing of harvest. The reset of the phenology value to zero at the coldest day of the year is plausible.

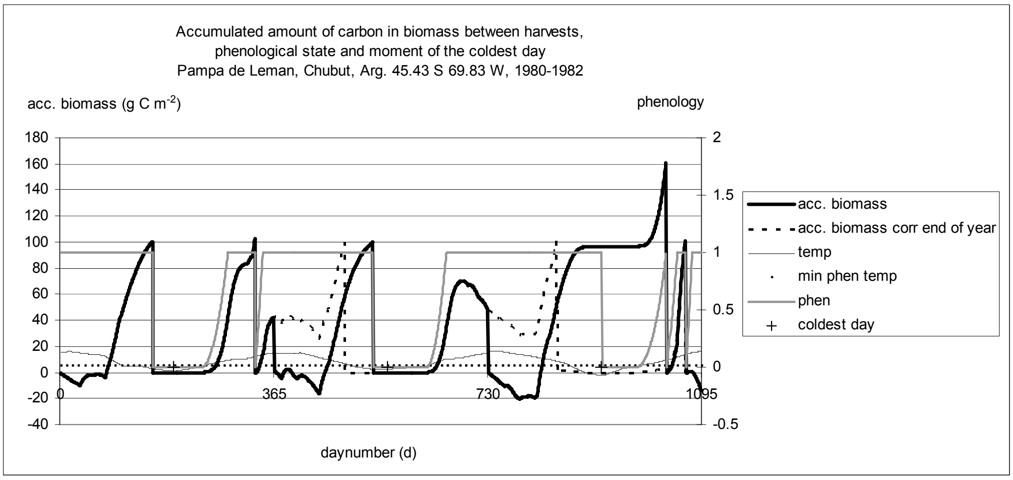


Figure 47 The amount of carbon in accumulated biomass, amount of carbon in accumulated biomass when the biomass is not set at zero at day 365 but only at a harvest moment, temperature, and base temperature for phenology increment, phenology and coldest day of South America for 1980 to 1982.

4.3.5.6 Summary of a harvest

Harvest conditions are met when the incremented biomass reaches 100 g C m^{-2} and the value of phenology is one. If the allocation parameter is very small, all incremented biomass is allocated to the roots. Next, a parameter i_leaf is calculated with the allocation parameter and the amount of incremented carbon and the carbon in existing leaves and roots. This parameter may be negative or positive. When positive all the i_leaf carbon is added to the already existing amount of leaf carbon and the carbon in the roots is supplemented with (biomass-i_leaf) than half of the amount of carbon in the leaves is allocated to harvested carbon and the remainder stays in the leaves.

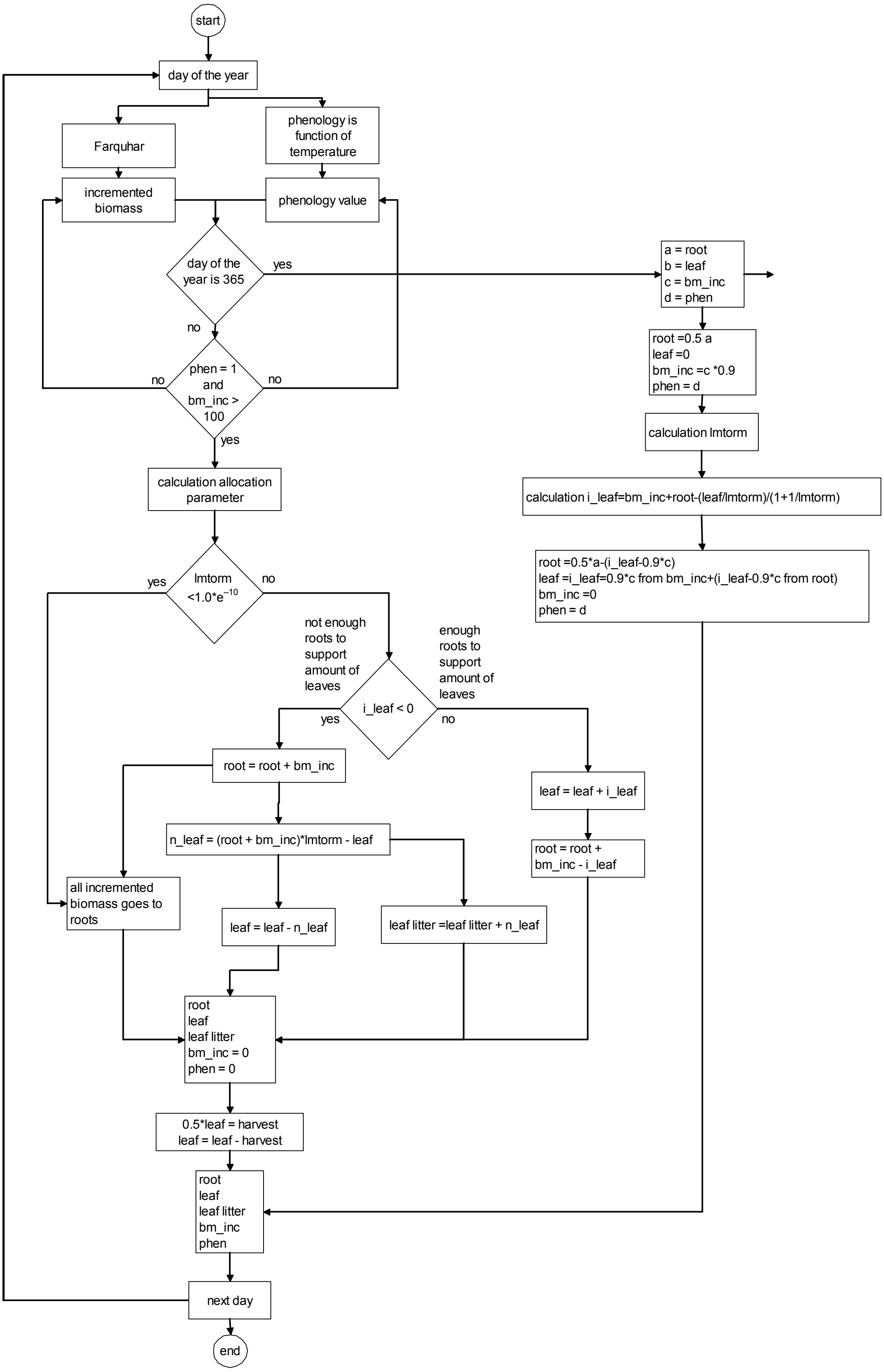


Figure 48 Flowchart of the biomass allocation process at a harvest moment.

If the i_leaf parameter is negative (i_leaf becomes n_leaf), all accumulated biomass is allocated to the roots (a negative value of i_leaf means there are not enough roots to support the leaves). The calculated amount of carbon (n_leaf) is subtracted from the existing amount of carbon in the leaves and allocated to leaf litter (to reduce the amount of leaves Figure 48). At the end of the year, half of the carbon in leaf goes to harvest and the other half goes to leaf litter. Half of the carbon in the root goes to root litter. If any biomass is formed after the last harvest, 10% goes to leaf litter. With a new value of the calculated allocation parameter `lmtorm`, and the remainder of newly formed biomass and the remainder of carbon in root, the fraction of carbon to the leaves is calculated (i_leaf). This amount of carbon in the leaves is supplied by the remainder of newly formed biomass since the last harvest and (part of) the remainder of carbon in the roots.

4.3.6 Specific leaf area (SLA)

The specific leaf area starts with a default value of 0.5 (Table 8). During a model run, the specific leaf area (*SLA*) for the different plant functional types is calculated as:

$$SLA = 2.0 * 10^{-4} . \frac{e^{6.15}}{(12 a_{leaf})^{0.46}} = 0.04111 \qquad (\text{m}^2 \text{ leaf g}^{-1} \text{ C leaf})$$

The parameter a_{leaf} is the life span of leaves in years, which depends on plant functional type (PFT). In LPJmL, a_{leaf} (yr) has a value of 0.5 for grasses. With this value of $a_{leaf,}$ the SLA changes in 0.04111. In Sitch *et al.* (2003) a_{leaf} (yr) has a value of one for temperate and tropical herbaceous plant types. This gives a value of *SLA* of 0.029.

With the amount of carbon in the leaves (after harvest, g C m^{-2} ground) and the specific leaf area (*SLA*), the leaf area index (*LAI*, m^2 leaf m^{-2} ground) is calculated.

SLA of perennial grasses has values between 0.03 and 0.06, but annuals have higher levels between 0.06 – 0.08 (Garnier *et al.*, 1997). A higher *SLA* will lead to a higher *LAI* and to more self-shading (which is not part of LPJmL).

4.3.7 Leaf area index (LAI)

In LPJmL, the leaf area index (*LAI*) is calculated as:

LAI = amount of C in leaves (g C m^{-2} ground)* *SLA*. (m² leaf m^{-2} ground)
actual_LAI = amount of C in leaves (g C m^{-2} ground)* *SLA**`phen`

As the *SLA* is a fixed value between harvests, the *LAI* depends directly on the value of the phenology and the amount of carbon in the leaves after the moment of harvest. In Figure 49, the value of *LAI* is given in time. The PFT dependent *LAI* is used to calculate the foliage projective cover (*FPC*, 4.2.3).

$$FPC = nind * (1 - e^{(-kLAI)}) \qquad \text{(section 4.2.3)}$$

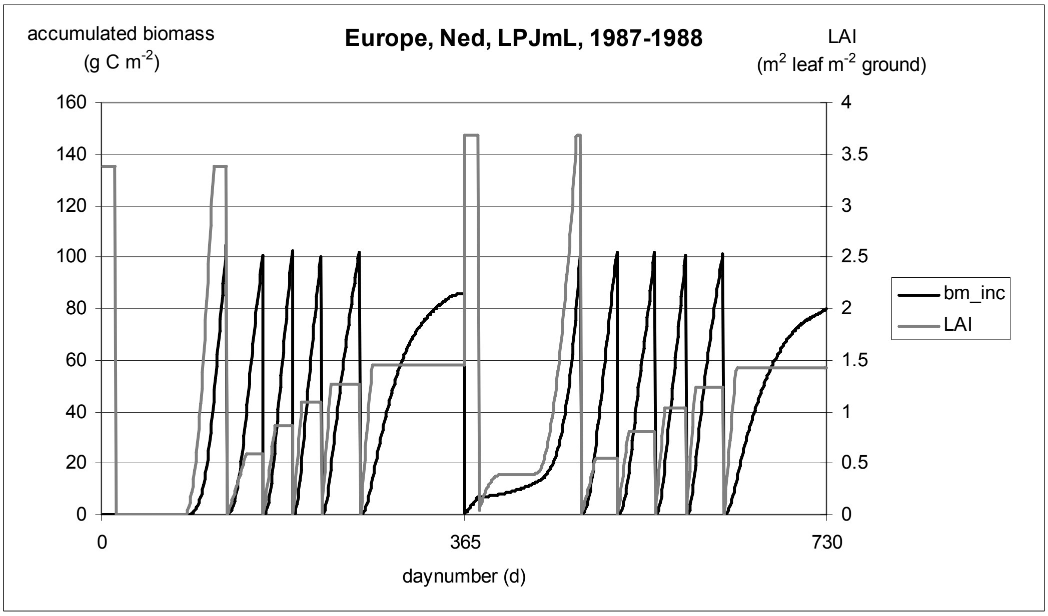


Figure 49 Increment of biomass and calculated LAI, the Netherlands, 1987–1988.

4.3.8 Decay of litter

Each PFT has an associated above- and belowground litter pool. As litter decomposes a fraction, representing the highly labile fraction, is respired into the atmosphere as CO_2. The remainder is divided between the intermediate and slow soil organic matter (SOM) (Foley, 1995). The litter pool is assigned a decomposition rate at 10°C of 0.35 yr^{-1} while the intermediate and slow SOM pools are assigned decomposition rates at 10°C of 0.03 and 0.001 yr^{-1}.

On a daily basis, small parts of the leaf and root litter are allocated to a carbon pool in the soil called `decay_litter`. The amount of allocated carbon is determined by:

$$\texttt{decay\_litter = 1.0 - e}^{(-\ (\texttt{k\_litter10*response}))}$$

with

`k_litter10 = (0.3/NDAYYEAR)` (d^{-1} °C)

`NDAYYEAR = 365` number of days in a year

`response = gtemp_soil * ((1.0 - e(-w[0]))/MOIST_DENOM` (°C)

with

`MOIST_DENOM = 0.632` which is $1.0-e^{(-1)}$ (–)

`gtemp_soil = temp_response(soiltemp(soil,climbuf))` (°C)

$$\texttt{temp\_response} = e^{(308.56*(\frac{1}{56.02}-\frac{1}{temp+46.02}))}$$ (Sitch *et al.*, 2003) (°C)

`temp` = the soil temperature dependent of soil characteristics, the air temperature of previous days and a lag factor (°C).
308.56, 56.02 and 46.02 are temperatures in K (Lloyd & Taylor, 1994) (Figure 32).

The value of the parameter `decay_litter` is the same for leaf and root litter. Every day the same amount of root litter and leaf litter allocates to the carbon pool called `decom` (`decom.bg` for belowground root litter and `decom.ag_grass` for aboveground grass litter) (see Figure 51). The above and belowground decom pools are added in the parameter `littersum`.

From the `littersum` carbon pool a fixed fraction (0.7) is converted to CO_2. The remainder (0.3) goes to the next carbon pool called `cflux_litter` (Foley, 1995). With a fixed ratio `cflux_litter` is divided into a fast (0.98 * carbon pool littersum) en a slow (0.02 * carbon pool littersum) decaying part. The amounts are added to the fast and slow decaying pools of the previous day. Every day part of the fast and slow decaying pools decomposes depending on the amount of carbon in the pools and the same response function as the decay_litter parameter but with a different k_soil factor.

`cflux_soil_slow = cpool.slow`$*(1.0-e^{(-(\mathrm{k\_soilslow10}*\mathrm{response}))})$ (g C)
`cflux_soil_fast = cpool.fast`$*(1.0-e^{(-(\mathrm{k\_soilfast10}*\mathrm{response}))})$

`k_soilfast10` = (0.03/NDAYYEAR)
`k_soilslow10` = (0.001/NDAYYEAR)

The carbon flows of litter and decaying carbon pools are given in Figure 51.

4.3.9 Non irrigation

For calculations of grassland production with LPJmL, only the rainfed option is open. The motivation is that only in very intensive production systems irrigation of grassland is an option and the amount of irrigated area is limited.

4.3.10 C_3/C_4

In LPJmL the distinction between C_3 and C_4 grasses is based on the average minimum temperature over 20 years (parameter `temp_min20`). When this parameter is lower than 15.5 LPJmL calculates the carbon flows for C_3 grass, when the parameter is higher than 15.5 LPJmL calculates for C_4 grass. For most of the regions, this matches with the data. However, there are places where LPJmL selects a C_3 where a C_4 is given in the experimental data.

C_3/C_4 choice

When the difference between maximum and minimum temperature is large it is possible that LPJmL selects a C_3 instead of the expected C_4 grass because value of the parameter `temp_min20` gets under the threshold value of 15.5 °C. An example is the Kurukshetra location in India with the dominant grass species *Panicum miliare* (C_4). The average minimum temperature over 20 years is just below 15.5. When LPJmL is run with the standard threshold of 15.5, the calculated aboveground matter (black diamond Figure 50) is lower than the measured amount of aboveground grass matter (open diamonds). When the standard threshold is altered to 12.5, this forces LPJmL to calculate for C_4, the calculated aboveground matter increases (black line Figure 50). For 1971, the production levels of measured and calculated biomass matches, for 1970 the C_4 is still too low; there are still other factors responsible for the low production of LPJmL like the allocation ratio and maybe the factor alpha_a (4.2.4).

It is also possible that the chosen temperature threshold is not applicable for these circumstances. In Sage *et al.* (1999) C_4 plant species dominate in open landscape of monsoon-climates of India and Africa where the warm season is wet, but the cool season dry (Figure 11A). According to Long (1983), C_4 plants are rare at altitudes and latitudes where growing season temperatures are less than an average of approximately 16 °C and minimum midsummer temperatures average less than 8 °C to 12 °C. It may be suggested that for the monsoon areas not the average minimum temperature is important, but the average temperature of 16 °C and midsummer temperatures.

The temperature is the main directing requirement for the occurrence of C_4 grasses, but the timing of the precipitation is of importance too. The total precipitation does not appear to matter as regions in South Africa receiving 100 mm or 1000 mm of rain can be exclusively C_3 or C_4 depending on the timing of the precipitation (Vogel *et al.*, 1978). The timing of precipitation may be taken into account as well to improve the predictability of C_4 grasses in monsoon regions by LPJmL because the distribution of rain over the year is known already.

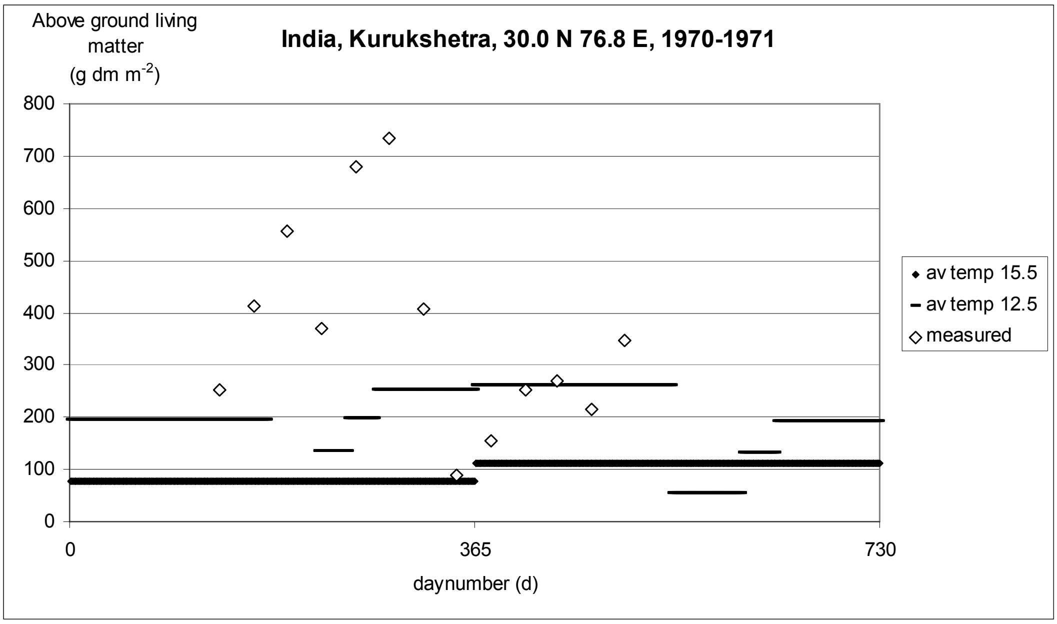


Figure 50 Amount of dry matter in leaves when two thresholds for the 20 year average of the minimum temperature for the Kurukshetra location in India.

C_3/C_4 phenology and output

The value of parameter `phen` increases when the air temperature rises above the threshold temperature of 5 °C in LPJmL. The threshold temperature is the same for C_3 and C_4 grasses meaning that the phenology is the same for C_3 and C_4 grasses (see 3.1.4). This may need further investigation.

There are locations where C_3 and C_4 grasses grow together like in grid cells in Africa (Kenya) and Australia. When the option SINGELCROP and GRASSLAND is chosen in LPJmL, this causes problems with the output of grid cells where both C_3 and C_4 species grow together. As the output is constructed now, it is not possible to see PFT daily output data like amount of carbon in leaf, root and biomass increment for C_3 or C_4 separately. These data are calculated for every PFT separately and they should be sent to the output in that way. The PFT dependent output data in LPJmL are given on a yearly basis only.

4.3.11 Fire

There is a possibility in LPJmL to run the model with burning of litter. This is an interesting feature because fire plays an important role in many grassland systems. The conditions for fire are NATURAL vegetation and a reasonable minimum threshold of 200 g C m^{-2} litter from trees and grasses. The only effect of burning in the model is a decrease in litter. In reality, fire returns nutrients like phosphorus and potassium to the soil, which is not accounted for in the current model version.

4.4 C-cycle in grass production

To get a better idea of the timing of the processes indicated in previous sections carbon flows (C-flow) are derived for key moments in LPJmL. There are four C-flows, a daily C-flow, a C-flow when there are not enough roots and when there are enough roots to support the amount of leaves and a C-flow at the end of the year (day 365).

With the use of carbon flows, carbon balances may be derived. The carbon balance provides insight of the amount of carbon per input and output source in a grid cell at a certain moment in time (Table 9).

Input of the balance is the growth of the vegetation by the photosynthesis processes (and sometimes existing leaf and root matter) and output contains sources like the amount of C lost by respiration, harvest of grass (and animal products) and decay of fast and slow soil C-pool and litter. Although there are four C-flows only for the end of the year a C-balance is derived. To be able to understand the yearly C-balance it is necessary to understand the daily C-flows and C-flows at harvest times as well.

Table 9 Carbon balance of a grid cell (g C m^{-2})

	Input source	**Amount**	**Output source**	**Amount**
	leaf (t–1)		leaf (t)	
	leaf litter (t–1)		leaf litter (t)	
	root (t–1)		root (t)	
	root litter (t–1)		root litter (t)	
	increase of biomass (t–1)		harvest (t)	
	soil C-pool fast(t–1)		soil C-pool fast(t)	
	soil C-pool slow(t–1)		soil C-pool slow(t)	
			decay soil C-pool fast (t)	
			decay soil C-pool slow (t)	
			decay litter (t)	
difference				
total:				

4.4.1 The daily C-flows

The daily C-flow exists of two pieces (Figure 51) of the grid C-balance in Table 9. One piece is the input of de C-balance (biomass growth or increment). The second piece is a part of the output of the C-balance, the decay of litter and C-pools in the soil.

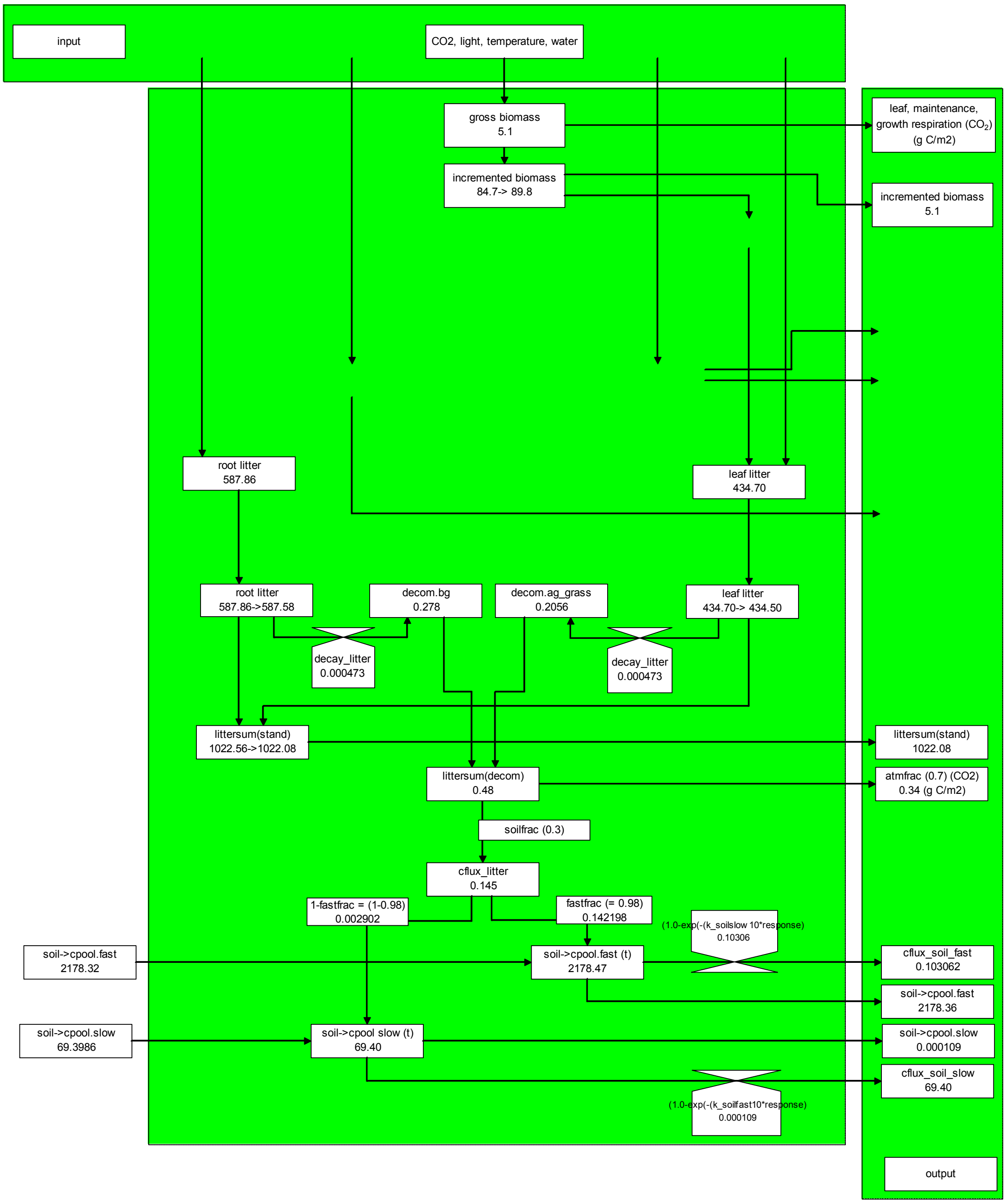


Figure 51 Chart of the two daily carbon flows, the growth of biomass and the decay of leaf and root litter and fast and slow carbon pools in the soil. The white squares are active.

The daily flows are not connected on a daily basis but both alter on a daily basis. The amount of C in the net biomass is building up and the amount C in litter from leaf and root and the C-pools in the soil is decreasing.

4.4.2 The C-flow at harvest time

At the time of harvest (see 4.3.5.4) when the i_leaf is negative (shortage of root mass), the calculated net accumulated amount of C in biomass is allocated to the roots. In Figure 52 the allocation of accumulated carbon is drawn in a diagram.

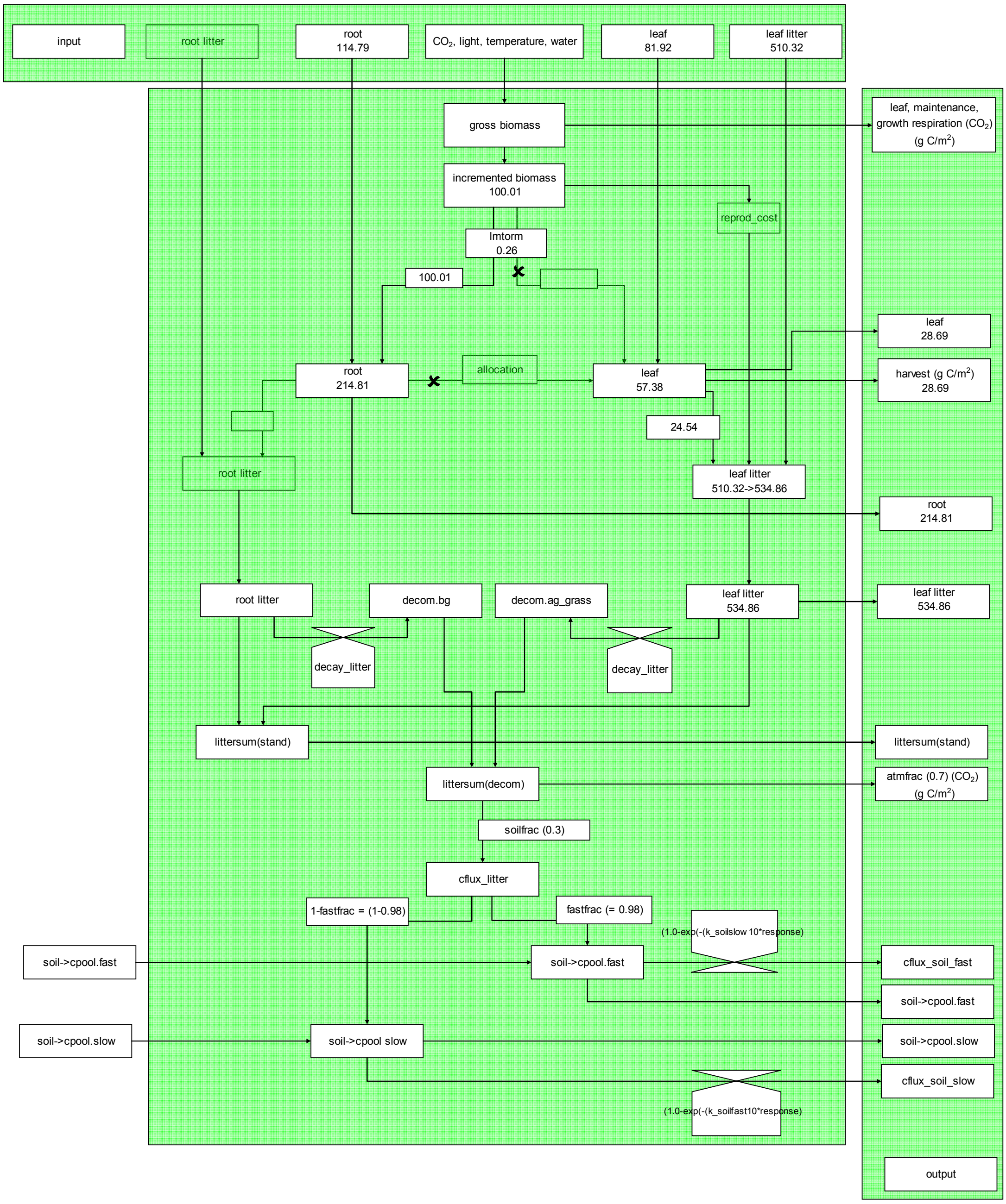


Figure 52 The carbon flow at a harvest moment when the parameter i_leaf is negative.

When the value of parameter i_leaf is positive at the time of harvest, the calculated net accumulated amount of C in biomass allocates to roots and leaves (Figure 53).

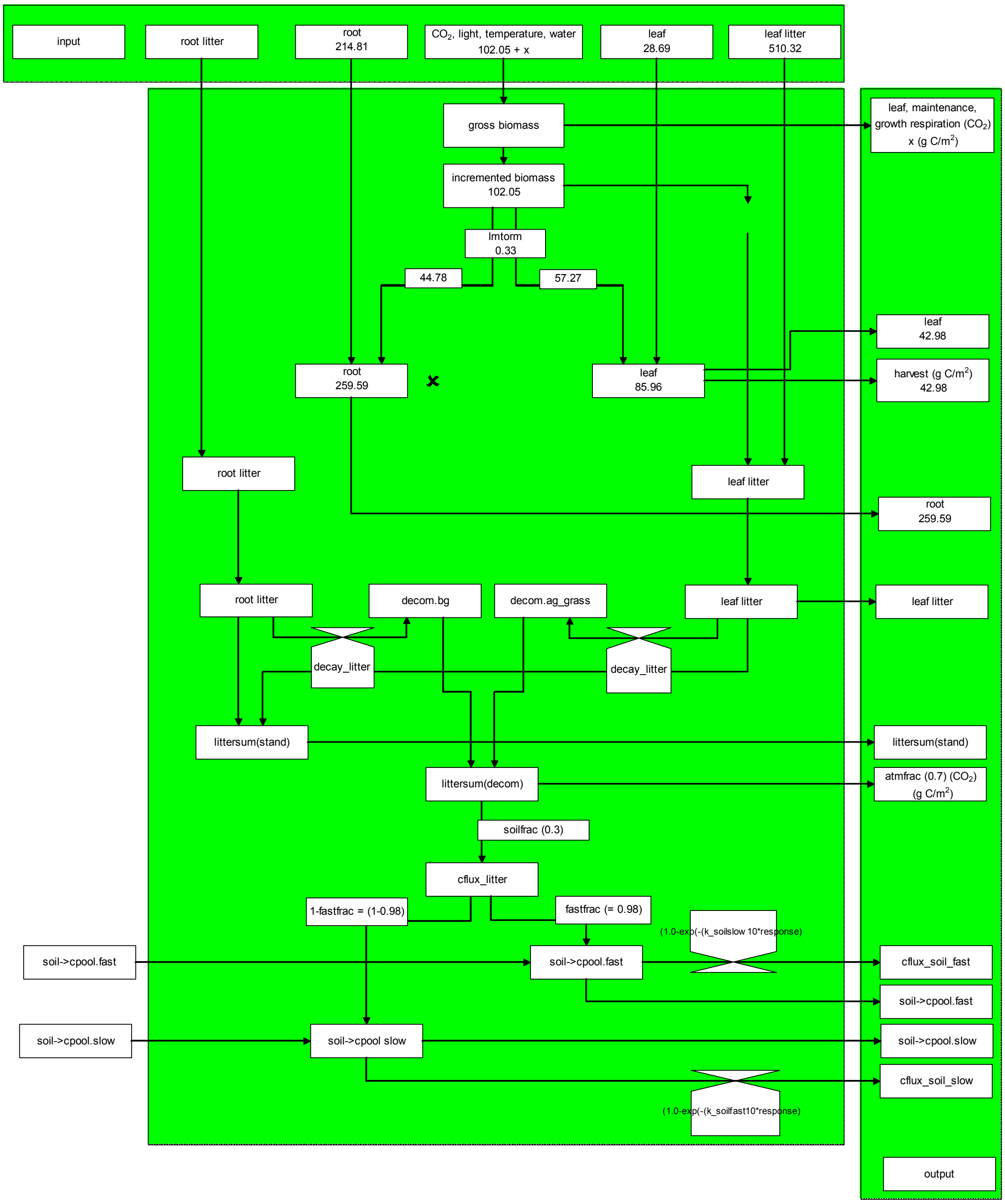


Figure 53 The carbon flow at harvest moment, when the parameter i_leaf is positive.

In the model, the allocation parameter depends on a fixed allocation parameter (set to 0.75, Sitch *et al.*, 2003) and the amount of water in the soil. After allocation, the amount of carbon accumulated in biomass is set to zero. At harvest time, a fixed amount of leaves (50%) is harvested. After the harvest, the building of biomass starts again.

4.4.3 The C-flow at the end of the year (day 365)

The next C-flow shows the amount of carbon inherited from the previous year, formed during the year and distributed to the various pools and passed on to the next year.

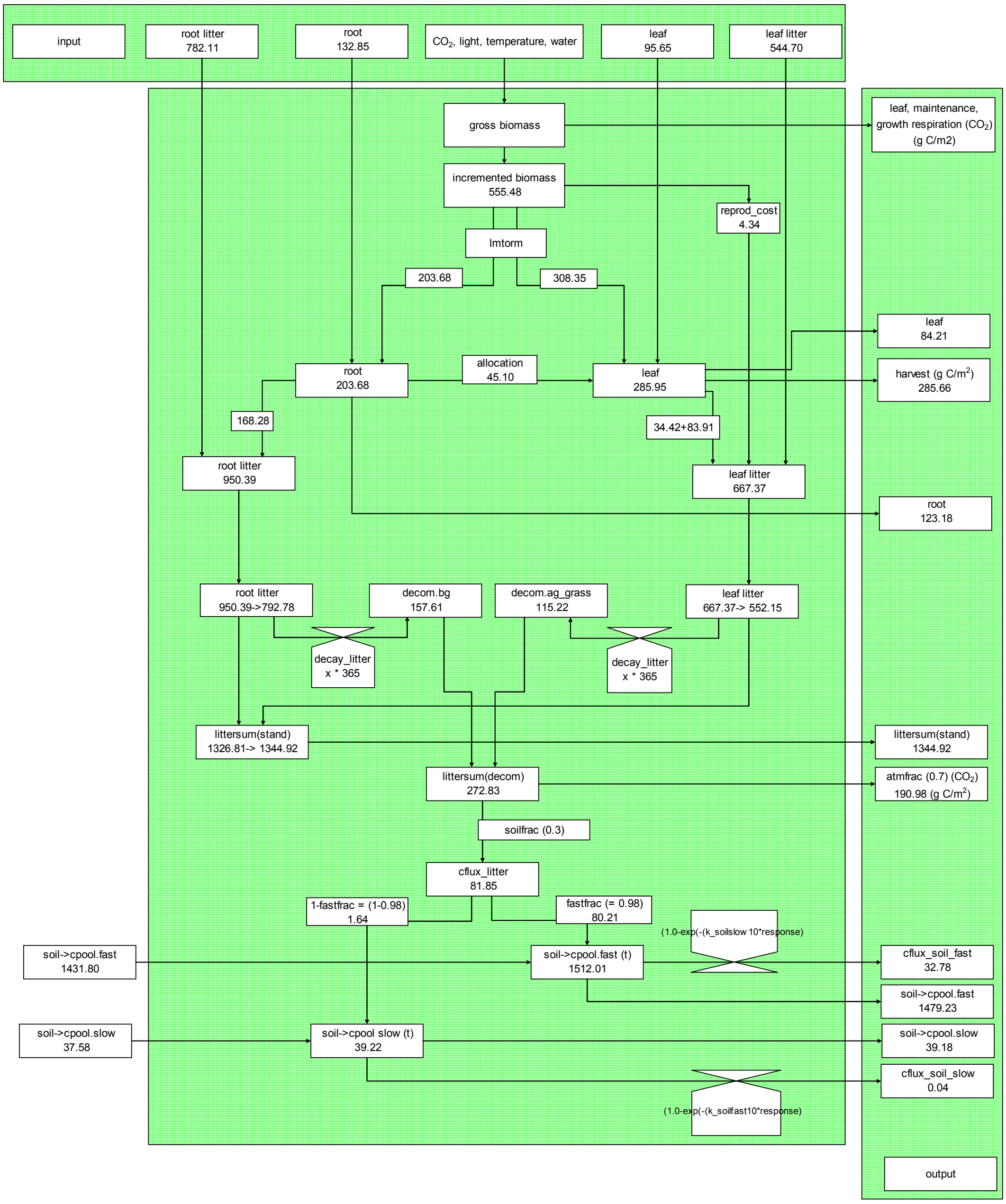


Figure 54 Carbon flow between two years in LPJmL.

The yearly C-flow provides the amount of carbon used in the yearly C-balance. There are tow presentations of the C-balance.

To get an idea of the amount of carbon involved, one presentation shows the total amount of input, output and increase of biomass (Table 10). To get an idea about the differences per source, the other presentation shows the increase in biomass (input) and the difference in amount of the individual sources (input – output) during the year.

At the end of the year, LPJmL allocates 10% of the incremented biomass after the last harvest, to leaf litter for reproduction reasons (Sitch *et al.*, 2003). If there has not been a harvest during the year, all biomass is sent to litter and there is no harvested grass.

Table 10 C-balance of total amount of carbon for one year (1981) of the Netherlands (g C m^{-2}).

	Input source	Amount	Output source	Amount
	increase of biomass (t–1)	555.48		
	leaf (t–1)	95.65	leaf (t)	84.21
	leaf litter (t–1)	544.70	leaf litter (t)	552.15
	root (t–1)	132.85	root (t)	123.18
	root litter (t–1)	782.11	root litter (t)	792.78
	soil C-pool fast(t–1)	1431.80	harvest (t)	285.66
	soil C-pool slow(t–1)	37.58	soil C-pool fast(t)	1479.23
			soil C-pool slow(t)	39.18
			decay soil C-pool fast (t)	32.78
			decay soil C-pool slow (t)	0.04
			decay litter (t)	190.98
difference				
total:		3580.17		3580.19

Table 11 C-balance with the difference of input and output sources for one year of the Netherlands, 1981 (g C m^{-2}).

	Input source	Amount	Output source	Amount
	increase of biomass	555.48	leaf	–11.44
			leaf litter	7.45
			root	–9.67
			root litter	10.67
			harvest	285.66
			soil C-pool fast	47.43
			soil C-pool slow	1.60
			decay soil C-pool fast	32.78
			decay soil C-pool slow	0.04
			decay litter	190.98
difference				
total:		555.48		555.50

5 Simulation of grassland productivity with LPJmL

5.1 Regional comparison of calculated and measured grassland production

5.1.1 Introduction

For the main grassland regions of the world a comparison is made between the calculated amount of aboveground biomass by LPJmL and measured amount of aboveground biomass. These data are collected by NASA and made available as NPP MULTI-BIOME: global primary production data initiative. The experimental sites are given in Figure 55.

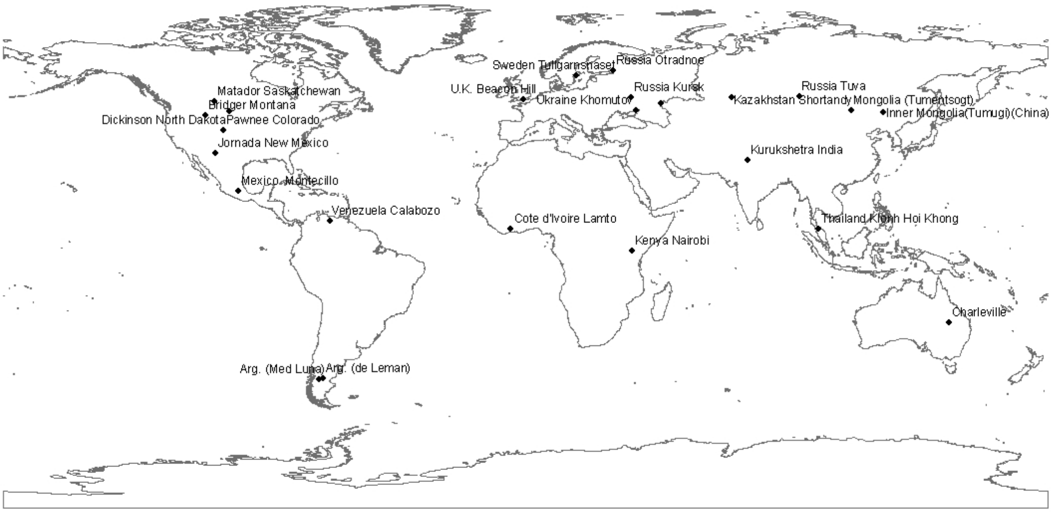


Figure 55 Locations used to compare the calculated water limited total, above and belowground biomass production by LPJmL with local measured data.

The NPP Database contains documented field measurements (actual data) of NPP for global terrestrial sites compiled from published literature and other data sources. The NPP Database contains biomass dynamics, climate and site-characteristics data geo-referenced to each intensive site. A major goal of the data compilation is to use consistent and standard well-documented methods to estimate NPP. The database contains 37 grassland sites, of which the 23 largest sites are used for comparison.

Most data from the NASA-database contain information about aboveground biomass (AGbiomass), litter, standing dead matter and 'total aboveground matter'. The total aboveground matter is the sum of the AGbiomass, litter and standing dead matter. Some sites provide measurements of belowground biomass (BGbiomass). Detailed information is given in Annex 2. All parameters from LPJmL are converted from g C m^{-2} to g dm m^{-2} by dividing by 0.45, because the data in the NASA-database are given in g dm m^{-2}.

In Figure 56 the mean annual temperature and mean annual precipitation of all the experimental sites are given. The locations represent reasonably well all (natural grass) habitats, from warm humid to dry cold and dry warm.

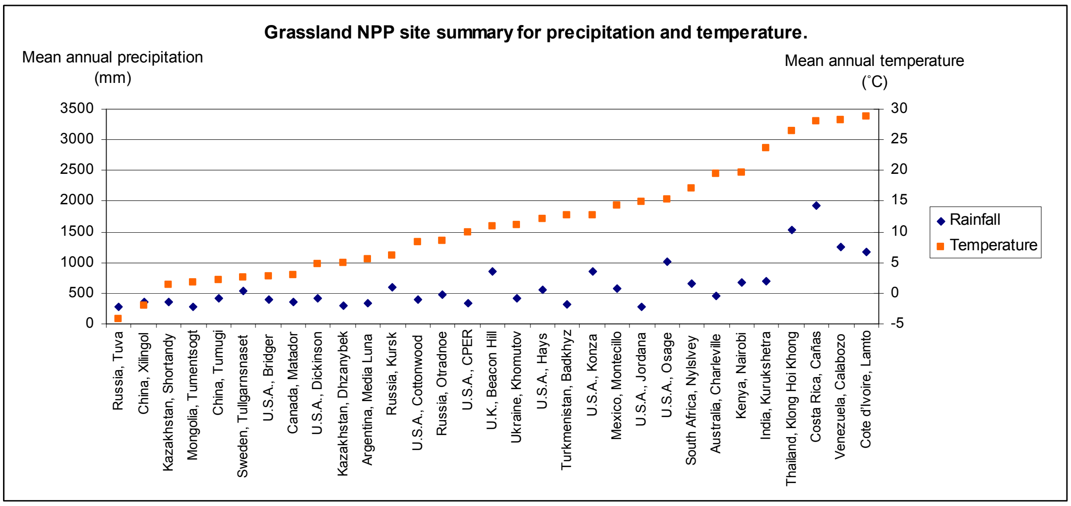


Figure 56 Mean annual precipitation and mean annual temperature of the experimental sites considered for comparing grassland measurements and calculated biomass production by LPJmL.

At all locations, the living aboveground biomass (dry matter) is measured monthly during the growing season. These data are used for comparison with the LPJmL living aboveground production (amount of carbon in living leaves).

In LPJmL, the photosynthesis procedure calculates the daily carbon production. This daily carbon production is accumulated for periods between harvests. At a harvest moment and at the end of the year (4.3.5.4) LPJmL calculates how much accumulated carbon will be allocated to the existing amount of carbon in the leaves, roots and litter. Hence, the value of amount of carbon in the leaves does not change between harvests and causes straight lines in representations of carbon in the leaves as in Figure 57.

The comparison of measured and calculated amount of carbon in living leaves is hampered by two other characteristics of LPJmL:

- the amount of carbon in the leaves in the output is half the amount of carbon produced, because half of the carbon is the leaves is harvested;
- in LPJmL, the senescence is reduced to a moment when there is a not enough root biomass to support the amount of leaves (may be the first harvest) and the end of the year (day 365).

The first problem can be solved. At a harvest moment, the amount of incremented carbon is allocated to leaves and roots and at the end of the harvest moment, half of the amount of carbon in the leaves is harvested. To get the total aboveground production, the amount of carbon in the leaves has to be multiplied by two.

It is not possible to solve the second problem completely. In LPJmL, the senescence of the grass is not calculated during the growing season but, apparently, an amount of carbon of the leaves is sent to litter when the leaf/root ratio is too high (may be the first harvest) and at the end of the year. This causes a continuing increase of the calculated amount of carbon in the leaves during the growing season whereas the measured amount of carbon in living leaves reduces towards the end of the year (Figure 57).

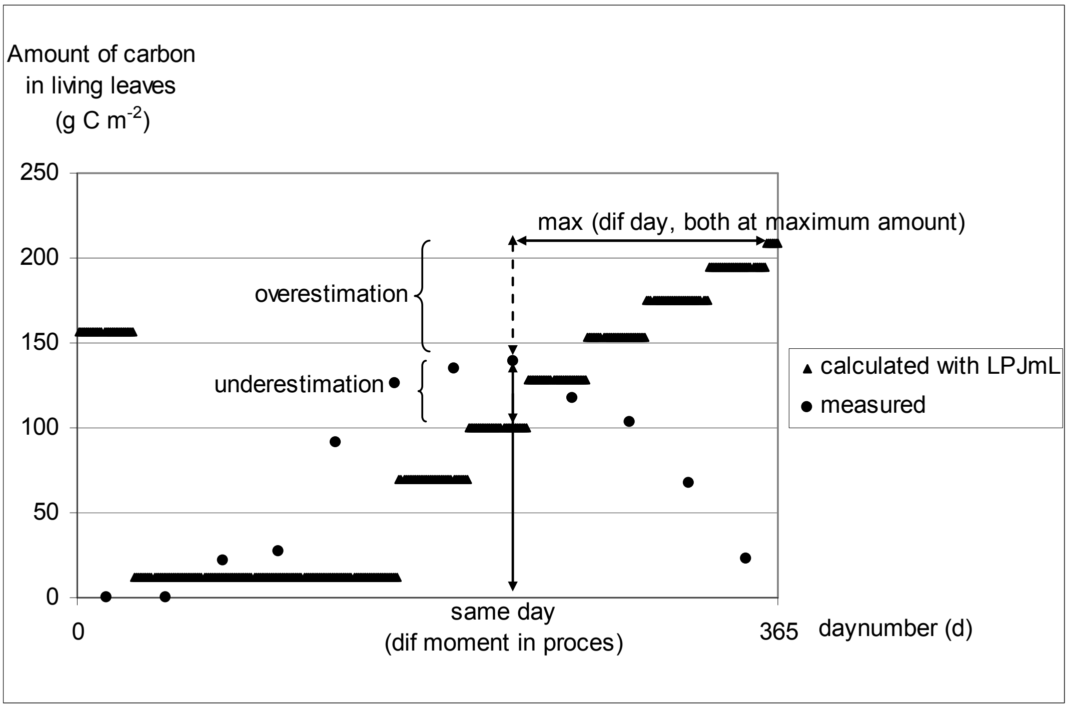


Figure 57 Measured and calculated amount of carbon in living leaves (g C m^{-2}).

The comparison between measured and calculated carbon production may take place on the same day (but with different amounts of carbon produced, Figure 57 'same day') or the maximum production of the calculated and measured data can be compared (on different days) (Figure 57, max). This prohibits a correct comparison of measured and calculated carbon:

- on the same day, because the calculated value has not reached its maximum on the day the measured value has and this suggests an incorrect underestimation by LPJmL;
- at maximum production, because than the timing is wrong.

For the two approaches, the relative difference between the calculated and measured amount of carbon in the living leaves for the 23 regions is calculated and presented in Figure 58.

The relative difference is calculated as:

relative difference = (calculated-measured)/measured

- on the same day (same day) and
- measured maximum aboveground biomass in comparison with the maximum aboveground biomass LPJmL calculates for that year (max).

The data are sorted for increasing differences in 'max'.

Table 12 Continent and land, site name, location, soil type, mean annual precipitation (mm), elevation (m), mean annual temperature (°C), percentage of sand, silt and clay, pH, soil C content 0–20 cm (g m^{-2}) and soil N content 0–20 cm (g m^{-2}).

Continent, land	Site Name	Location	Soil type	m.a.p. (mm)	el. (m)	m.a.t. (°C)	sand	silt	clay	pH	soil C 0–20 cm (g m^{-2})	soil N 0–20 cm (g m^{-2})
Africa, Cote Ivoire	Lamto	6.22N 5.03 W	ferruginous hydromorphic pseudogley	1170	300	28.8	0.85	0.1	0.05	6	1800	150
Africa, Kenya	Nairobi	1.33 S 36.83 E	black clay grumsolic vertisol	680	1600	19.7	0.13	0.17	0.7	7.5	3500	367
Asia, Thailand	Klong Hoi Khong	6.33 N 100.93 E	sandy	1540	30	26.4	0.58	0.4	0.02	5.5	–	–
Australia	Charleville	26.40 S 146.27 E	sandy red earth	489	304	19.4	–	–	–	–	–	165
Canada, Saskatchewan	Matador	50.70 N 107.72 W	brown clay, well drained	350	676	3	–	–	–	–	–	–
Central America, Mexico	Montecillo	19.46 N 98.91 W	solonet/entisol	590	2240	14.2	0.47	0.35	0.18	9	–	–
Central America, Venezuela	Calabozo	8.93 N 67.42 W	ultisol/oxisol	1257	98	28.3	0.51	0.22	0.27	4.1	–	–
China	Tumugi	46.1 N 123.0 E	chernozem/dark chestnut mollisol	411	191	2.1	0.35	0.32	0.33	–	–	–
Europe, Kazakhstan	Dzhanybek	49.33 N 46.78 E	heavy light-chesnut	274	20	5	0.28	0.28	0.44	7.8	3150	340
Europe, Kazakhstan	Shortandy	51.67 N 71.0 E	calciboroll/calciustosol	351	367	1.3	0.36	0.27	0.37	7.4	5600	500
Europe, Russia	Kursk	51.67 N 36.5 E	chernozem/haplaboroll	560	250	6.1	0.32	0.31	0.37	6.3	10430	910
Europe, Russia	Otradnoe No.1	60.83 N 30.25 E	soddy-podzolic, loamy	543	50	8.6	0.425	0.4	0.175	5.2	5780	460
Europe, Russia	Otradnoe No.2	60.83 N 30.25 E	soddy-podzolic, sandy	543	50	8.6	0.8	0.12	0.08	5	4030	280
Europe, Russia	Tuva	51.83 N 94.42 E	haplustosol/calciustosol	214	800	–4.3	0.74	0.17	0.09	7.3	4030	430
Europe, Sweden	Tullgarnsnaset	59.2 N 17.5 E	heavy clay	560	0	2.5	0.2	0.2	0.6	–	–	–
Europe, Ukraine	Khomutov	47.17 N 38.0 E	chernozem/vermiboroll	441	75	11.1	0.2	0.18	0.52	7.4	6930	580
Europe, United Kingdom	Beacon Hill	50.92 N 0.85 W	humic rendzina mollisol	873	205		–	–	–	7.8	–	–
Mongolia	Tumentsogt	47.4 N 112. E	dark chestnut mollisol	280	1100	1.7	0.6	0.2	0.2	–	7500	–
North America, Colorado	CPER Pawnee	40.82 N 104.77 W	sandy loam	310	1625	9.9	0.7	0.15	0.15	6.2	–	–
North America, Montana	Bridger	45.78 N 110.78 W	silty loam mollisol	925	2340	2.7	–	–	–	–	–	–
North America, New Mexico	Jornada	32.60 N 106.85 W	loamy sand aridisol	228	1350	14.9	–	–	–	–	–	–
South America, Argentina	Media Luna	45.60 S 71.42 W	typic cryoborols	374	630	5.5	1	0	0	6	–	–
South America, Argentina	Pampa de Leman	45.43 S 69.83 W	typic haplargids	150	400	–	–	–	–	–	–	–

It is to be expected that the calculated aboveground biomass by LPJmL overestimates the measured data because the calculations are only limited by water and not by nutrients or damage by pests and diseases. The simulation is better when the difference is above or close to zero. The rectangle gives the boundaries of –0.2 to +0.5. It may be expected that the overestimation should be less for developed areas and higher for developing areas because of improved management.

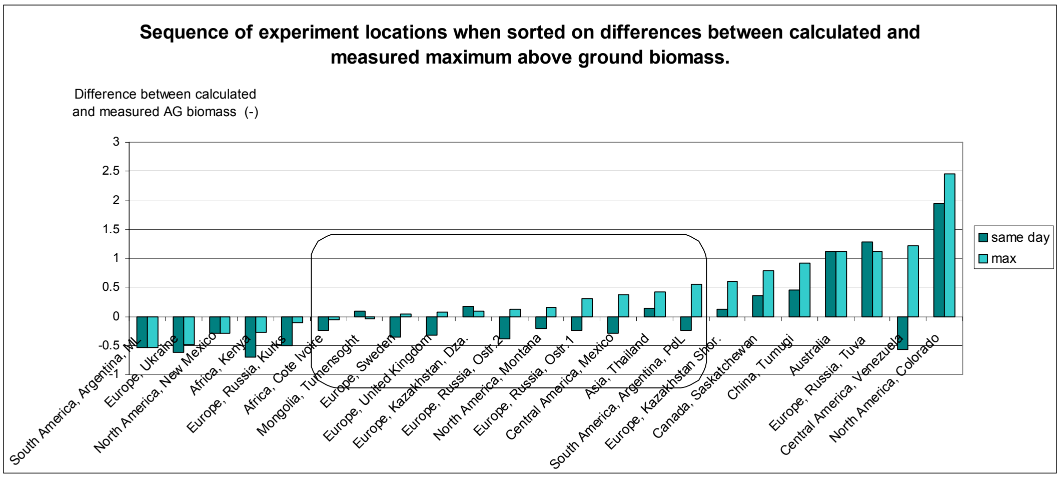


Figure 58 Difference between calculated and measured maximum aboveground biomass on the same day (same day) and measured maximum aboveground biomass in comparison with the maximum aboveground biomass as calculated by LPJmL for that year (max) per region, data sorted for 'max'.

There is an underestimation of the calculated aboveground biomass by LPJmL for Argentina, Ukraine and Kursk, New Mexico, Kenya and Ivory Coast. This may be the result of the management factor *alpha*$_a$ (see section 4.2.4).

There is an expected overestimation by LPJmL between measured and calculated maximum aboveground biomass in developed areas like North America and Europe but also in Central America, Venezuela.

There is a high overestimation by LPJmL between measured and calculated max aboveground biomass in developing or more remote areas like Africa and South America, but also in Canada, hence there are exceptions on the assumption made above for developed and developing areas suggesting that other factors play a role (like soil type).

In Figure 59 the difference between calculated and measured maximum aboveground biomass (max) is sorted and plotted against the soil type of the experimental regions. There is underestimation by LPJmL on soils with more organic matter. As expected, there is more under and over estimation for more extreme soils like the very heavy black clay grunsolic vertisol or the sour oxisol or dry loamy sand aridisol. The overestimation of LPJmL seems to increase with increasing coarseness of the soil (pers. comm. B. Janssen). The overestimations of grass production on coarse soils suggests a too high available water capacity calculated by LPJmL for there areas. This aspect needs further investigation.

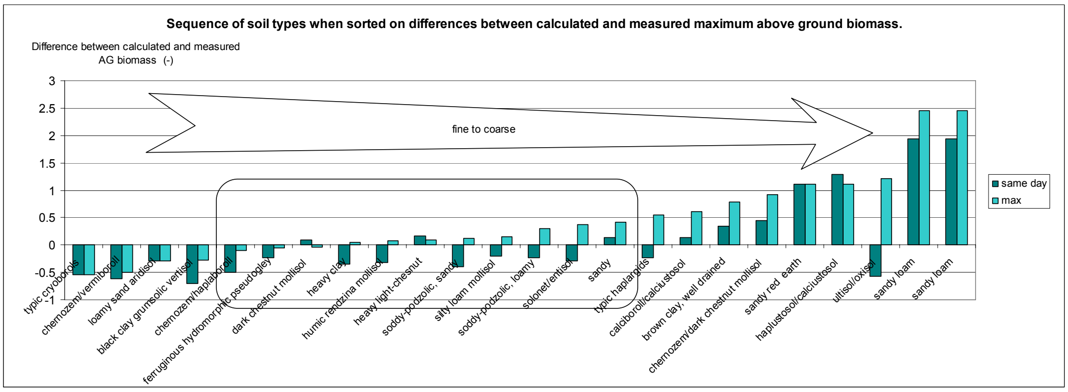


Figure 59 Difference between calculated and measured maximum aboveground biomass on the same day (same day) and measured maximum aboveground biomass in comparison with the maximum aboveground biomass LPJmL calculates for that year (max) per soil type sorted for 'max'.

In the following sections, the calculated values by LPJmL and measured data are compared per experimental site. Because the production is given in g dm m^{-2} rather than g C m^{-2} in the remainder of the text biomass (production) will be used instead of carbon (production).

5.1.2 Africa (savanna's)

5.1.2.1 Ivory Coast, Lamto 1969 – 1987

Description

Productivity of a humid grass savanna was determined at the Lamto study site operated in collaboration with CNRS (Centre Nationale de Recherche Scientifique) - École Normale Supérieure, Paris, France. Measurement of monthly dynamics of aboveground plant matter (i.e. live biomass and dead matter for some years, total biomass in other years), and total roots (live + dead), were monitored from 1969 to the present. Net primary production has been estimated for both above and belowground, although more data is available on the former.

The 2500 hectare Lamto Research Station (6.22 N 5.03 W) is situated 200 km north of Abidjan, near the town of Divo, at the southern edge of the humid savanna belt bordering the forest. The savanna is characterized by annual burning during the dry season in February, and by its high efficiency of nitrogen utilization. Nitrogen is remobilized from senescing leaves, and is very rapidly assimilated from decomposing plant residues without entering the soil pool of mineral nitrogen. The grass savanna occurs within a mosaic of grass, shrub, and tree savannas distributed according to drainage, slope and micro-topology.

Discontinuous data are available 1969–1986, including the effects of annual burning. Total net primary production (NPP) of the grass savanna has been estimated at 2150 g m^{-2} yr^{-1} of which 1320 g m^{-2} yr^{-1} (61%) is belowground production. Mean annual precipitation is 1170 mm and the elevation is 300 m. According to Modified Baily ecoregion classification, it is a humid savanna with dominant species Louditia Simplex (C_4). The plant lignin content is 10.6% and the long-term treatment is annual burning in February. The soil type is ferruginous hydromorphic pseudogley (sand/silt/clay 0.85/0.10/0.05) and pH 6.0. Soil carbon content is 1800 g C m^{-2} (0–20 cm) and the nitrogen content is 150 g N m^{-2} (0–20 cm) (Menaut, 1996).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1969–1987 for grid nr 24927. In Figure 60 the calculated and measured aboveground biomass (without dead standing matter and litter) is given. The amount of aboveground biomass calculated by LPJmL is lower than the measured data for three out of the four measured years.

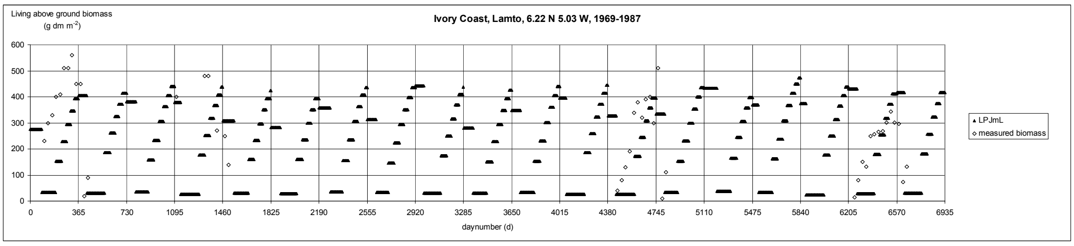


Figure 60 Measured and calculated living aboveground biomass for Lamto, Ivory Coast, 1969–1987 (g dm m^{-2}).

5.1.2.2 Kenya, Nairobi 1984 - 1994

Description

Net primary production of a savanna grassland in Nairobi National Park, Kenya, was determined from 1984 to 1994 by monitoring monthly dynamics of live biomass and dead matter, above and belowground, together with monthly litter bag estimates of decomposition rates above and belowground (see Figure 61). The method for calculating net primary production accounted for simultaneous growth and death, and carbon flows to all trophic levels. Work was carried out under the United Nations Environment Program (UNEP) Project on "Primary Productivity of Grass Ecosystems of the Tropics" and continued under subsequent UNEP and UK-ODA (Overseas Development Administration) sponsored international projects. The 100 m x 150 m study site is situated at the southern end of Nairobi National Park (1.33 S, 36.83 E), about 30 km southeast of Nairobi.

Figure 61 Dry season view of site exclosure fence, dry grass and young Acacia bush, Nairobi grassland site, Kenya. (Photograph taken February 1995 by A.D. Rosenschein, King's College London, UK).

The area is a typical East African grass savanna, which was used as grazing or holding ground for cattle for many years prior to the establishment of Nairobi National Park in 1946, when cattle grazing ceased and the area became a refuge for large herbivores. Net primary productivity was determined, initially under the auspices of a collaborative UNEP Project, since there was a lack of information on the productive capacity and carbon cycling of East African grasslands. Complete data are available from 1984 to 1986, including a very dry year (1984) and a wet year (1985). Data collection ceased in 1987, but resumed 1988–1991, including a separate plot, which was mown (clipped) to ground level in September 1989 (Kinyamario, 1996).

The data for Kenya are from the NPP study for comparison with models and estimation of NPP. Mean annual precipitation is 680 mm and the elevation is 1600 m. According to Modified Bailey ecoregion classification, it is a savanna with dominant plant species Themeda triandra (C_4) (Figure 62). The plant lignin content is 5–9% (mean 7%) and the long-term management is grazing with burning every 5 years. The soil type is black clay grumsolic vertisol (sand/silt/clay 0.13/0.17/0.70) and pH 7.5. The soil carbon content is 3500 g C m^{-2} (0–20 cm) and nitrogen content is 367 g N m^{-2} (0–20 cm).

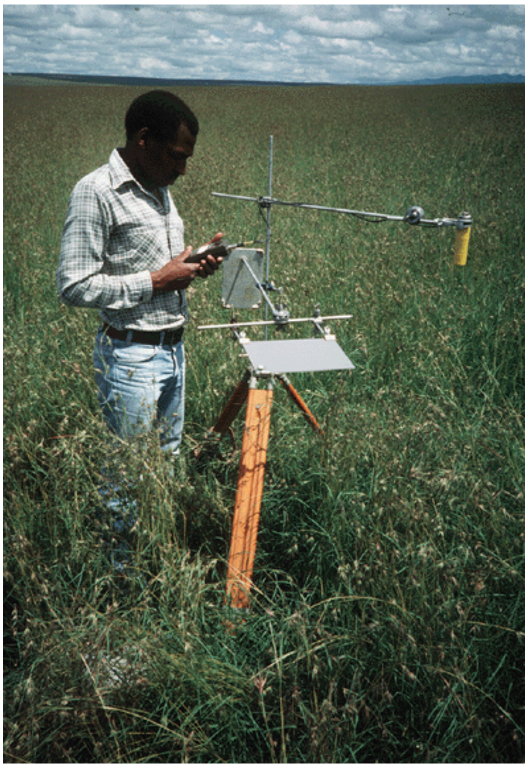


Figure 62 Canopy reflectance measurement within the Nairobi grassland site, Kenya. (Prof. Jenesio Kinyamario, University of Nairobi, is using a red/near-infrared spectral ratio meter. Photograph taken May 1986 by Dr. J.M.O. Scurlock, ORNL).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1984 – 1994 for grid number 37658. The total accumulated biomass production of LPJmL is compared with the sum of living above and belowground measured biomass (Figure 63). The calculated total biomass by LPJmL gives an expected overestimation of the measured total living biomass.

In Figure 64 the calculated and measured aboveground living biomass for Nairobi is given. LPJmL underestimates the amount of biomass in the leaves. In Figure 65 the calculated and measured amount of biomass in living roots for Kenya is given. The calculated amount overestimates the measured values and supports the underestimation of calculated biomass to the leaves. The underestimation of biomass the leaves may be caused by a too low allocation of biomass to the leaves.

For this location, LPJmL calculates values for C_4 and C_3 grasses. Because LPJmL is run for grassland only, only one plant functional type (PFT) is shown in the output, C_4 overwrites the C_3 data. When LPJmL is run for all PFT and CFT this problem does not occur.

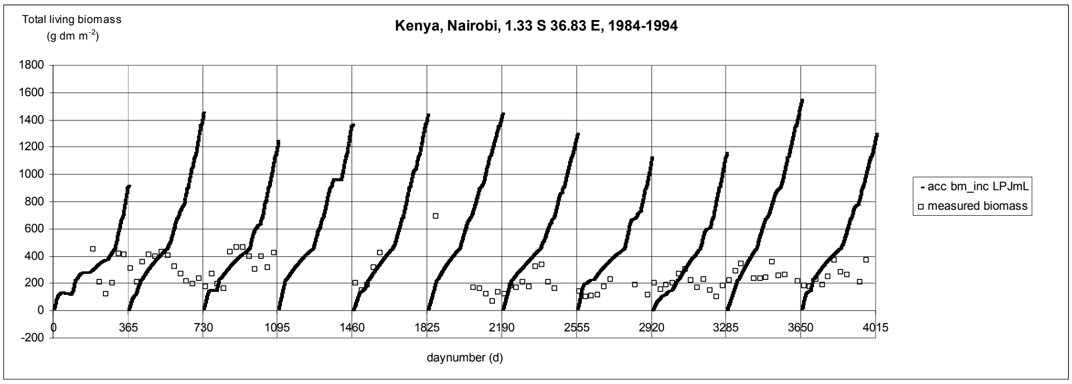


Figure 63 Calculated total biomass by LPJmL and measured total biomass (without standing dead matter and litter or dead roots) for Kenya, Nairobi, 1984–1994 (g dm m^{-2}).

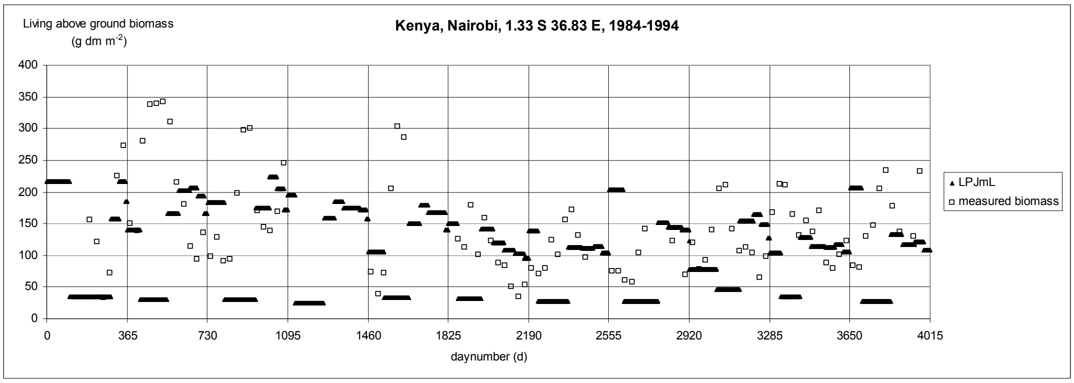


Figure 64 Measured and calculated aboveground biomass in Nairobi, Kenya from 1984 – 1994 (g dm m^{-2}).

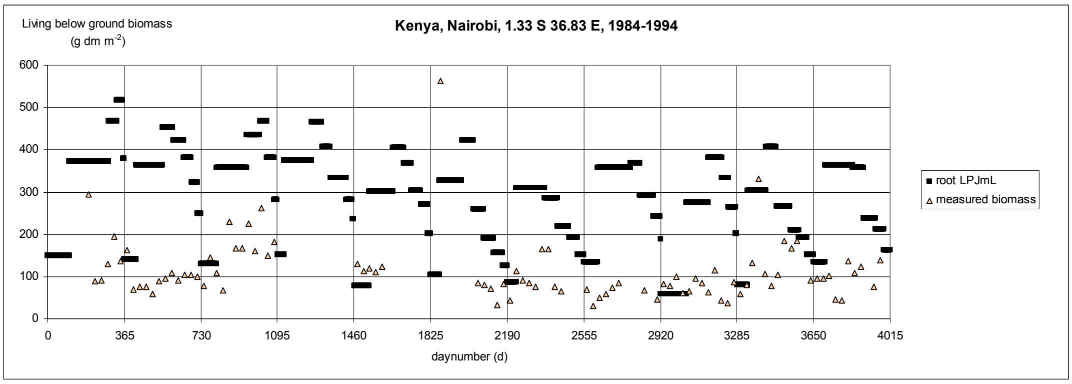


Figure 65 Measured and calculated amount of living belowground biomass by LPJmL for Kenya, Nairobi, 1984–1994 (g dm m^{-2}).

5.1.3 Asia (steppe)

5.1.3.1 China, Tumugi

Description

Biomass dynamics and productivity of meadow steppe grasslands were studied from 1981 to 1990 at Tumugi, Xingan League, in eastern Inner Mongolia, China. Measurements of aboveground and belowground live biomass were made monthly throughout the growing season (April to November), by clipping 1 m^2 quadrates and sampling 1 m^2 soil pits to a depth of 1.0 m. The Tumugi study site (approximately 46.1 N 123.0 E) is located about 60 km east of the city of Ulan Hot (approximately 300 km west of Harbin, China). It is representative of the meadow steppes of eastern Inner Mongolia, which cover about 50,000 km^2 in Inner Mongolia and is widely distributed in the Euro-Asian steppe zone (Figure 66).

With a continental sub-humid climate dominated by monsoon rains from April to September, these grasslands are grazed by sheep and cattle at moderate grazing intensity. Net primary productivity is known to vary considerably both spatially and from year to year as a function of precipitation and temperature. Data are available for three different steppe species: *Filifolium sibiricum, Stipa baicalensis*, and *Leymus chinense*. The 250 m x 40 m species plots have been fenced since 1976 for long-term monitoring of productivity, and each is divided into five 50 m x 40 m sub-plots for field sampling. Aboveground net primary productivity was estimated at 155 g m^{-2} $year^{-1}$ (average of three plots, based on peak aboveground biomass). Data on biomass dynamics have been compared with simulation results from the CENTURY model (Xiao & Ojima, 1999).

Figure 66 Inner Mongolian grassland in the People's Republic of China.
http://en.wikipedia.org/wiki/Grassland#Tropical_and_subtropical_grasslands

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1981 – 1990 for grid number 59486. The total accumulated biomass production of LPJmL is compared with the living above and belowground measured biomass (Figure 67). The calculated total biomass by LPJmL underestimates the measured total living biomass. This may be because the value of 0.5 of the management factor $alpha_a$ is too low for this region.

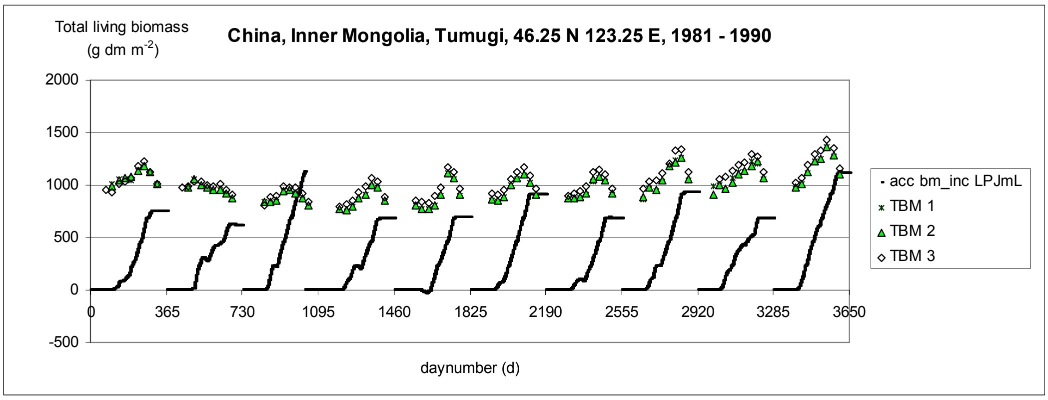


Figure 67 Calculated total biomass by LPJmL and measured total biomass (without standing dead matter and litter or dead roots) for Tumugi, China from 1981 – 1990 (g dm m^{-2}).

In Figure 68 the calculated and measured aboveground living biomass for Tumugi are given. LPJmL overestimates the amount of biomass in the leaves with an underestimation of total biomass. Hence, the allocation of biomass to the roots is underestimated as is clear from Figure 69.

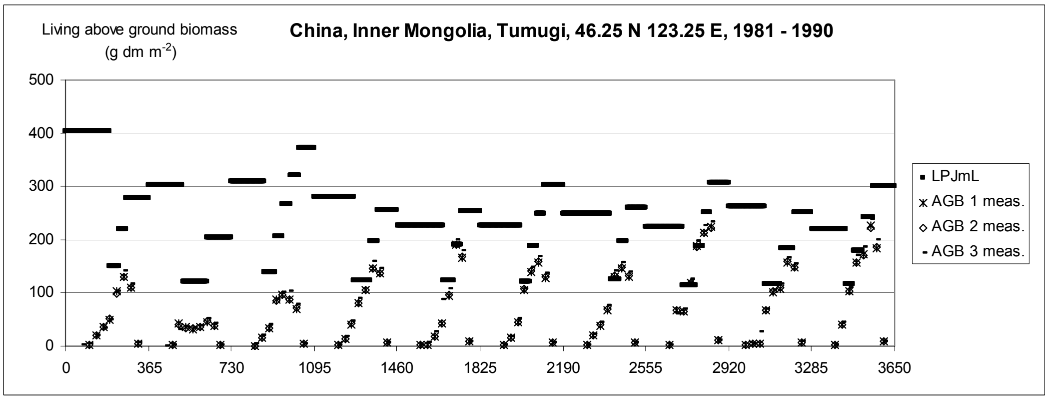


Figure 68 Measured and calculated aboveground biomass by LPJmL for Tumugi, China from 1981 – 1990 for three locations (g dm m^{-2}).

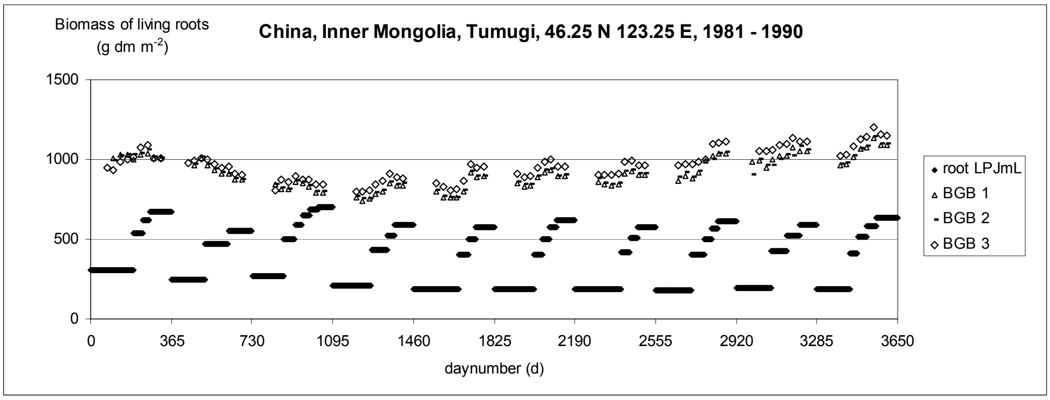


Figure 69 Calculated amount of biomass in living roots by LPJmL and measured belowground biomass (without dead roots) for China, Inner Mongolia, Tumugi, 1981–1990 for three locations (g dm m^{-2}).

5.1.3.2 Mongolia, Tumentsogt

Description

Productivity of steppe grassland was studied at the Tumentsogt Research Station of the Mongolian Academy of Science from 1982 to 1990. Measurements were made of peak aboveground live biomass for each year. The study site is located on the Eastern Mongolian Plains of the Tumentsogt sub-region (47.4 N 112.5 E), in Sukhbaatar administrative region. The Mongolian steppe occupies a major part of eastern Mongolia and northern China, characterized by an arid continental climate with most rain falling between June and August. Land use is dominated by grazing, historically by nomadic pastoralists and more recently for cooperative livestock production. Private livestock grazing has been increasing since 1990 (Togtohyn & Ojima, 1996).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1982–1990 for grid number 56306. In Figure 70 the calculated and measured aboveground living biomass for Mongolia, Tumentsogt are given. The calculated amount of dry matter in the leaves seems to match the measured amount. It is difficult to make a comparison between the calculation results and the measured data because with this low biomass production just one harvest and hence one allocation moment of biomass to leaves is calculated by the LPJmL model.

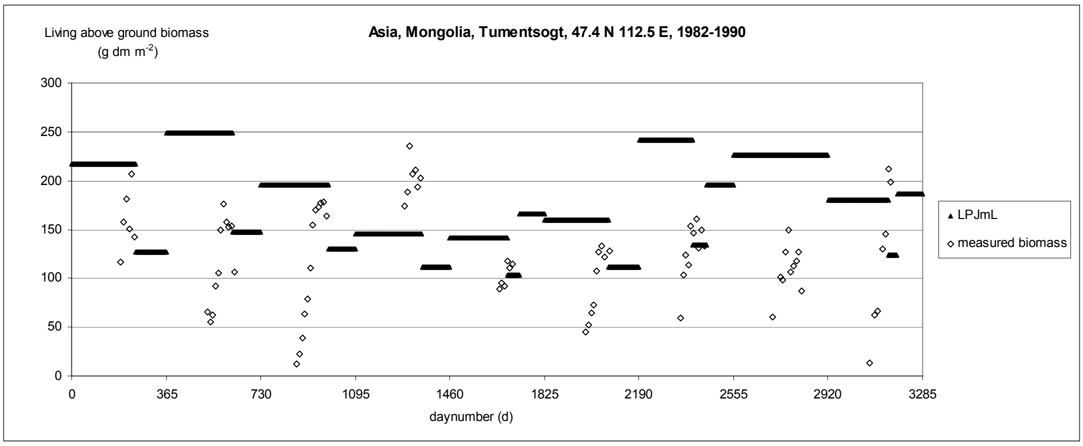


Figure 70 Measured and calculated living aboveground biomass in Tumentsogt, Mongolia from 1982 – 1990 (g dm m^{-2}).

5.1.3.3 Thailand

Description

Net primary production of humid savanna grassland was determined at the Klong Hoi Khong study site belonging to Prince of Songkla University in southern Thailand. Monthly dynamics of live biomass and dead matter, above and belowground, were monitored from 1984 to 1990, together with monthly litterbag estimates of decomposition rates above and belowground. The method for calculating net primary production accounted for simultaneous growth and death, and carbon flows to all trophic levels. Work was carried out under the United Nations Environment Program (UNEP) Project on "Primary Productivity of Grass Ecosystems of the Tropics" and has continued under subsequent UNEP and Thai- Austrian research projects.

The study site of several hectares is situated within a larger experimental field area (6.33 N 100.93 E), about 40 km south-west of Hat Yai. Ancient shifting cultivation in the region originally converted the tropical forest to a savanna-like tree-grass mosaic on poorer soils. The study site has supported a humid savanna for at least the last 50–100 years, and is typical of the semi-natural pastures in the Thai/Malaysian Peninsula which were until recently commonly maintained by burning. However, much of the region is now under pressure for conversion to arable crops or rubber plantations.

Net primary productivity was determined, initially under the auspices of an international collaborative UNEP Project, since there was a lack of information on the productive capacity and carbon cycling of the region. Complete data are available 1984–1990, including accidental burning in 1986 and 1989 (Kamnalrut, 1996).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1983–1990 for grid number 52978. The total accumulated biomass production of LPJmL is compared with the living above and belowground measured biomass (Figure 71). The calculated total biomass by LPJmL gives an expected overestimation of the measured total living biomass. In Figure 72 the calculated and measured aboveground living biomass for Thailand is given. LPJmL overestimates the amount of biomass in the leaves slightly.

In Figure 73 the calculated and measured amount of biomass in living roots for Thailand is given. For most years, the calculated amount of biomass in the roots matches the measured amount (exceptions 1989, 1990).

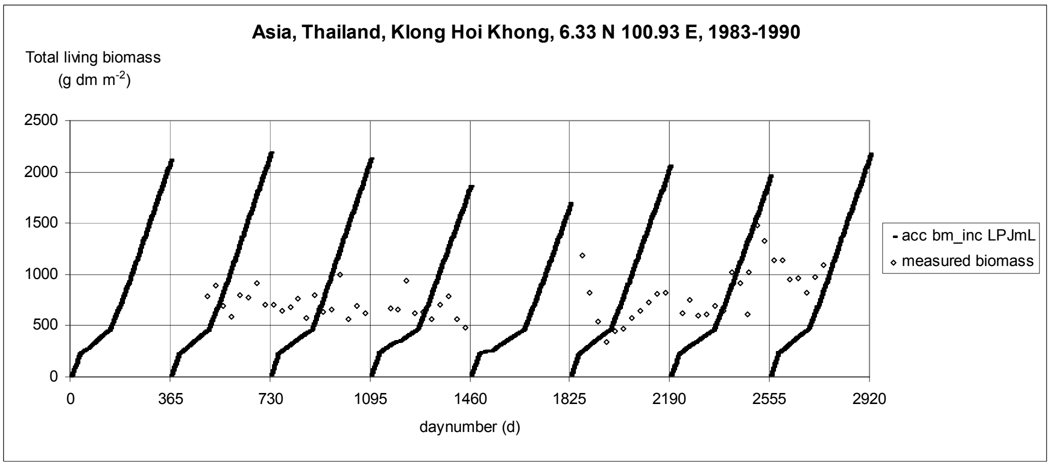


Figure 71 Calculated total biomass by LPJmL and measured total biomass (without standing dead matter and litter or dead roots) for Asia, Thailand, 1983–1990 (g dm m^{-2}).

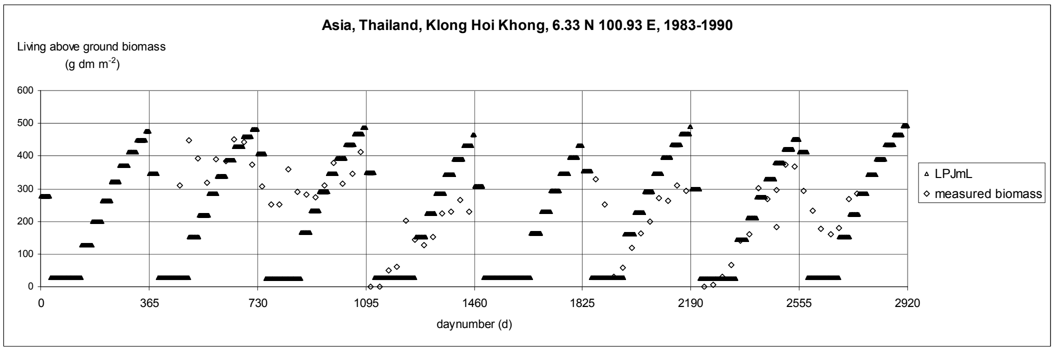


Figure 72 Two times the calculated amount of leaf and the measured aboveground biomass (g dm m^{-2}) in Klong Hoi Khong, Thailand from 1983 – 1990.

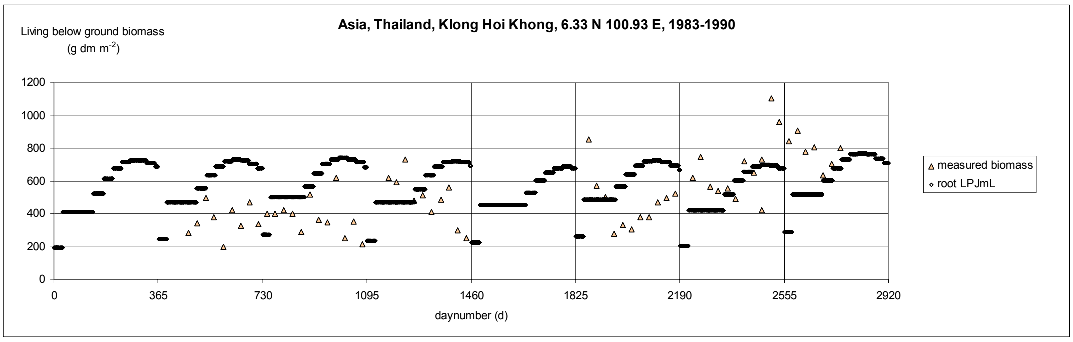


Figure 73 Calculated amount of biomass in living roots by LPJmL and measured belowground biomass (without dead roots) (g dm m^{-2})for Asia, Thailand, 1983–1990.

5.1.3.4 India, Kurukshetra

Description

Net primary productivity (NPP) was determined for tropical grassland at Kurukshetra University in northern India, for 1970 and 1971. NPP was calculated according to several methods, with preference shown for the estimate given by summing positive increases in biomass and accounting for mortality. Total NPP was estimated at 3538 g m^{-2} yr^{-1}, with aboveground NPP of 2407 g m^{-2} yr^{-1} and belowground NPP of 1131 g m^{-2} yr^{-1}. Work was carried out under the auspices of The Indian IBP program.

The 2–hectare Kurukshetra study site (29.97 N 76.85 E) was situated on the university campus in the district of Karnal, Haryana state, about 150 km north North West of Delhi. It had been maintained as grassland over the period 1950–1970, with little biotic interference apart from insect and small mammal herbivore. In general, the area is low-lying with little relief but a hummocky topography. The grasslands in this region originate from abandoned areas previously cleared for cultivation, and are maintained by grazing and annual burning. Climate is tropical monsoonal, with a rainy season from July to September, a cool dry season (October-February) and a hot dry season (March-May).

Detailed monthly data are available on aboveground biomass (14 species categories reported in literature), standing dead and litter, and total belowground matter. Additional data on solar radiation, canopy stratification, root distribution and estimated energy flows are reported in the literature (Singh & Yadava, 1997).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1970 and 1971 for grid number 47090. In Figure 75 the calculated and measured aboveground living biomass for Kurukshetra are given. The average minimum temperature over 20 years is lower than 15.5°C hence; LPJmL assumes a C_3 grass growth in this region (Figure 74 light gray line). The dominant species for this location is Panicum miliare (C_4) (Singh & Yadava, 1997). To force LPJmL to calculate the aboveground biomass for a C_4 grass the threshold temperature for C_3/C_4 is lowered to 12.5. The grass production of the C_4 grass is higher but still does not match the high measured values for living aboveground biomass. Another reason for lower biomass production may be the management factor of 0.5. However, even when alpha$_a$ is changed to 1 (black line) the calculated biomass by LPJmL underestimates the measured values.

The amount of calculated biomass in dead roots, 1500 g dm m^{-2}, is much higher then the belowground NPP of 1131 g m^{-2} yr^{-1} of the site description (Singh & Yadava, 1997), hence, the allocation of biomass to roots may be too high as well.

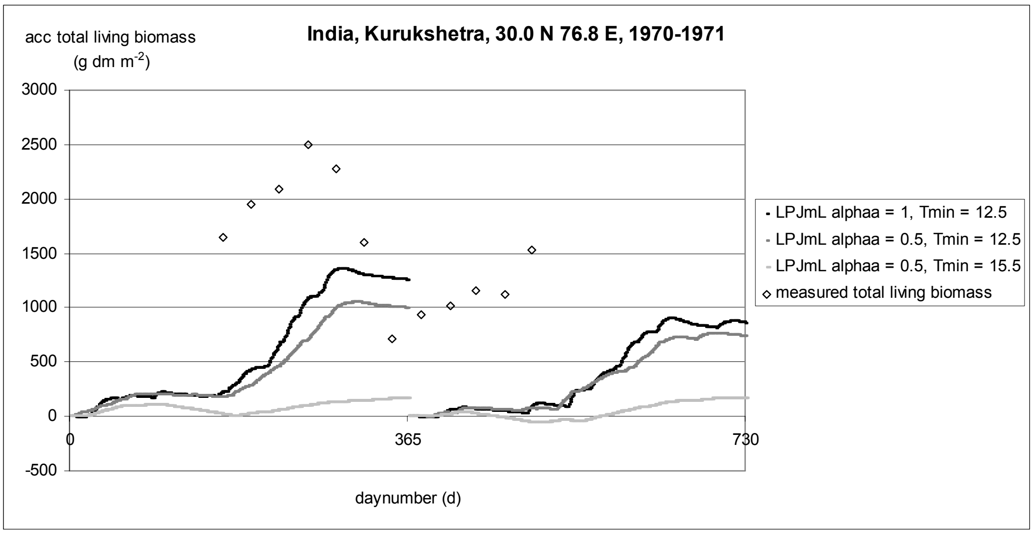


Figure 74 Calculated total biomass by LPJmL and measured total biomass (without standing dead matter and litter, and with living and dead roots) for India, Kurukshetra, 1970–1971. Calculations are made with alpha$_a$ = 0.5 (default) and = 1 and average minimum temperature = 15.5 (C$_3$) of 12.5 (C$_4$).

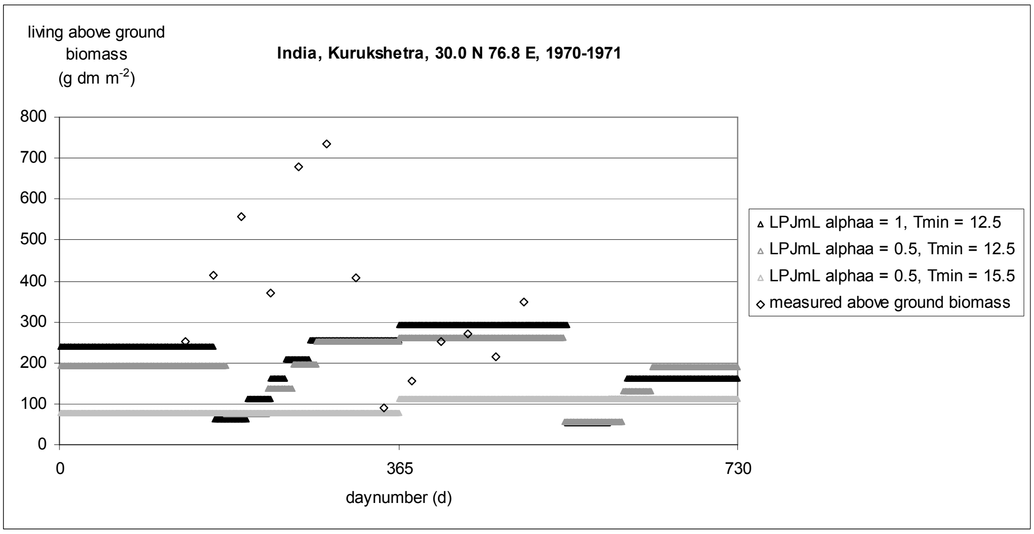


Figure 75 Calculated amount of biomass in leaves and the measured aboveground biomass (g dm m^{-2}) in Kurukshetra, India from 1970 – 1971. Calculations are made with alpha$_a$ = 0.5 (default) and = 1 and average minimum temperature = 15.5 (C$_3$) of 12.5 (C$_4$).

Although the position of Patancheru (and the environmental circumstances) is quite different from the Kurukshetra site a comparison with LINGRA has been made to get an idea of the reason of the underestimation of LPJmL. In Figure 76 the temperature and precipitation by LPJmL and LINGRA for the Patancheru site are given. There is a close match between these parameters.

In Figure 77 the calculated and measured aboveground biomass by LPJmL and LINGRA is given. Only in 1980, the calculated amount of leaf biomass by LINGRA has a lower value than the leaf biomass by LPJmL. This suggests a correct calculation of LPJmL for this spot of India and maybe for Kurukshetra as well or both models underestimate the production in India.

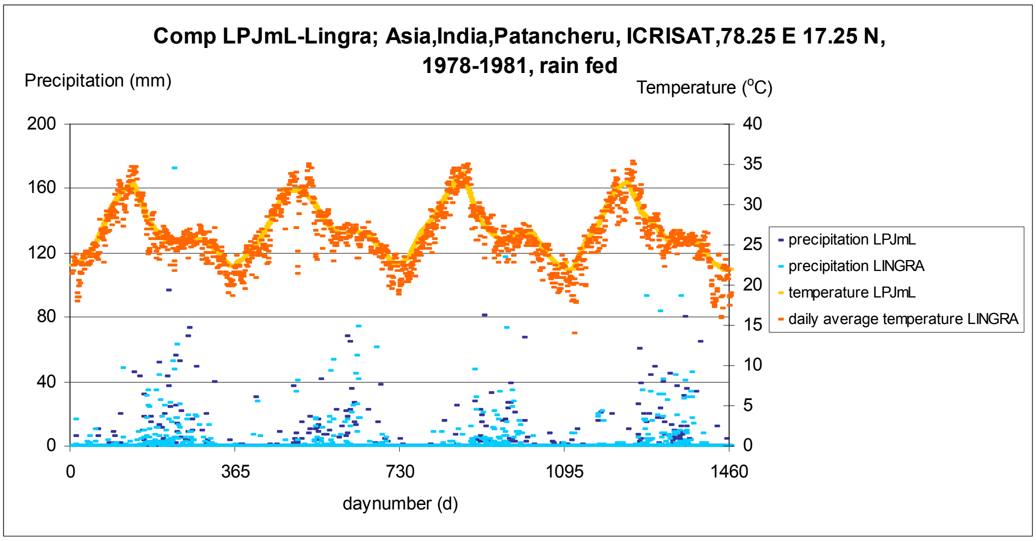


Figure 76 Estimated precipitation (mm) and temperature (°C) by LPJmL and LINGRA.

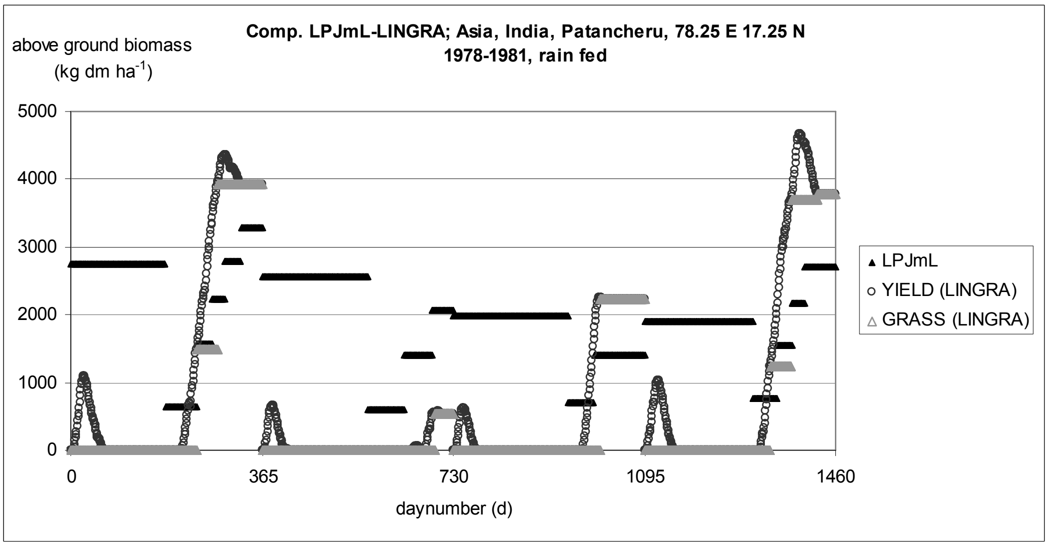


Figure 77 Calculated amount of biomass in leaves by LPJmL and LINGRA (YIELD) and harvested amount of biomass in leaves by LINGRA (GRASS) (kg dm m^{-2}) for Patancheru, India from 1978 – 1981.

5.1.4 Australia (savanna)

Description

Aboveground and belowground productivity of native C_3 grassland (Figure 78) and introduced C_4 grassland (Figure 79) were studied from 1973 to 1974 near Charleville in southern Queensland, northeast Australia. The study was carried out with a view to parameterising a simulation model of primary production and livestock carrying capacity. Measurements of aboveground and belowground standing crop (live + dead matter) were made every 2 weeks during the growing seasons - otherwise every 4 weeks - by clipping 1 m^2 quadrates and sampling 5 cm diameter soil cores to a depth of 40 cm. Both sites were mowed to a height of 4 cm at the beginning of the study (November 1973) to remove senescent material.

Figure 78 A naturally spread pasture under grazing in northern Australia. FAO pictures.

Figure 79 Cenchrus ciliaris cv. Gayndah (Gayndah buffel grass). Charleville, Queensland, Australia. Source: Tropical Grasses, FAO (1990); fao pictures.

The Charleville study sites, each of 0.7 ha, included a native perennial "mulga" grassland located within Charleville airport (26.40 S 146.27 E), about 1 km south of the town of Charleville, and a sown grassland dominated by *Cenchrus ciliaris*, about 25 km north of the town. Grazed mulga shrublands, containing *Acacia* shrubs together with a grass layer, comprise about 200,000 km^2 in southwestern Queensland. They are usually associated with red earth soils, which are characterized, by very low nutrient concentrations and a narrow range of available soil water. Peak aboveground standing crop at the end of the summer season was 122 g m^{-2} and 154 g m^{-2}, respectively, for the native and the introduced grass sites. Maximum belowground standing crop was markedly different, at 110 g m^{-2} and 400 g m^{-2}, respectively, suggesting a significant difference in shoot/root allocation. Net primary production was estimated as the sum of aboveground peak standing crop (live + dead) and root increment; figures were 182 and 319 g m^{-2} year^{-1} for the native and introduced grass sites, respectively. Additional data on litter production and nutrient dynamics are available for the native grassland site. Data on soil moisture, determined gravimetrically with each biomass harvest, are available in the literature (Christie, 1999).

The mulga ecoregion is a vast arid expanse that extends into the heart of Western Australia. The mulga tree, a drought-adapted acacia, dominates, and a variety of other plants grows in the understory. Annual rainfall is low, and the infrequent summer monsoons rarely extend as far as the southern portions of this ecoregion. Mulga trees may reach up to 5 m high in areas with good rainfall and emu bushes and hop bushes grow alongside cassias in the understory. In drier areas, mulgas are accompanied by a grassy understory and this vegetation is known as Wanderrie country. Here, mulga trees grow in dense stands in places where rainfall drainage is concentrated. Grazing and mining are the main land uses in this ecoregion, but most of the land is uninhabited. In areas where grazing with livestock occurs, mulgas may be overgrazed by livestock, especially by sheep.

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1973 and 1974 for grid number 64860. The total accumulated biomass production of LPJmL is compared with the sum of living above and belowground measured biomass (Figure 80). The average minimum temperature for the past 20 years is 11 °C hence LPJmL calculates the production for C_3 grasses. This coincides with the local C_3 grass species. LPJmL gives an expected overestimation of the measured total living biomass. In LPJmL the biomass increment is set back to zero at day one, this feature seems to cause a delay in biomass growth. The biomass calculated by LPJmL continues to grow when the measured biomass show a decrease after 17 May (day 137).

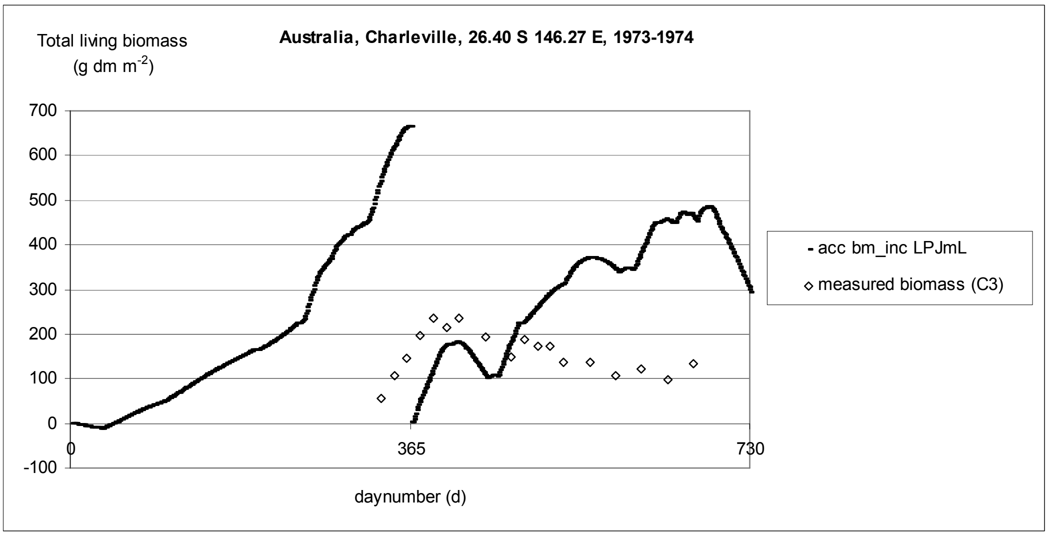


Figure 80 Calculated total biomass by LPJmL and measured total biomass (without standing dead matter and litter or dead roots) for Australia, Charleville, 1973 and 1974 (g dm m^{-2}*).*

In Figure 81 the measured and calculated amount of living aboveground biomass is given, LPJmL overestimates the measured values. The measured amount of aboveground biomass produced by introduced C_4 grasses (*Cenchrus ciliaris* or buffel grass) in the experiment (open diamonds) coincides better with the calculated amount of leaf matter by LPJmL (light gray diamonds) then the measured amount of aboveground biomass of C_3 grasses.

In Figure 82 calculated and measured amount of biomass in living roots for Australia is given. The calculated amount overestimates the measured values.

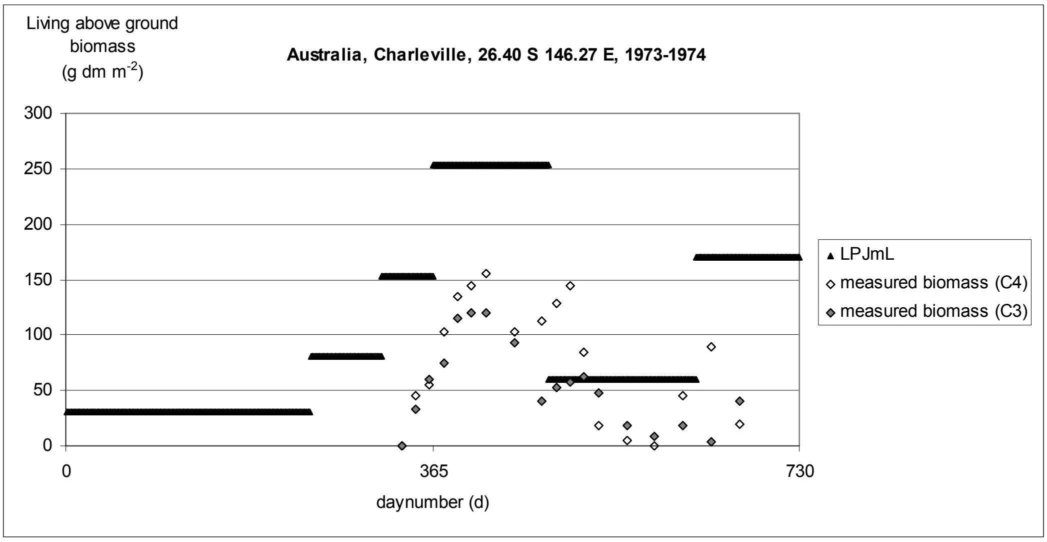


Figure 81 The amount of calculated leaf (LPJmL) and measured total aboveground biomass (inclusive litter) of C_4 and C_3 grass in Charleville Australia, 1973–1974.

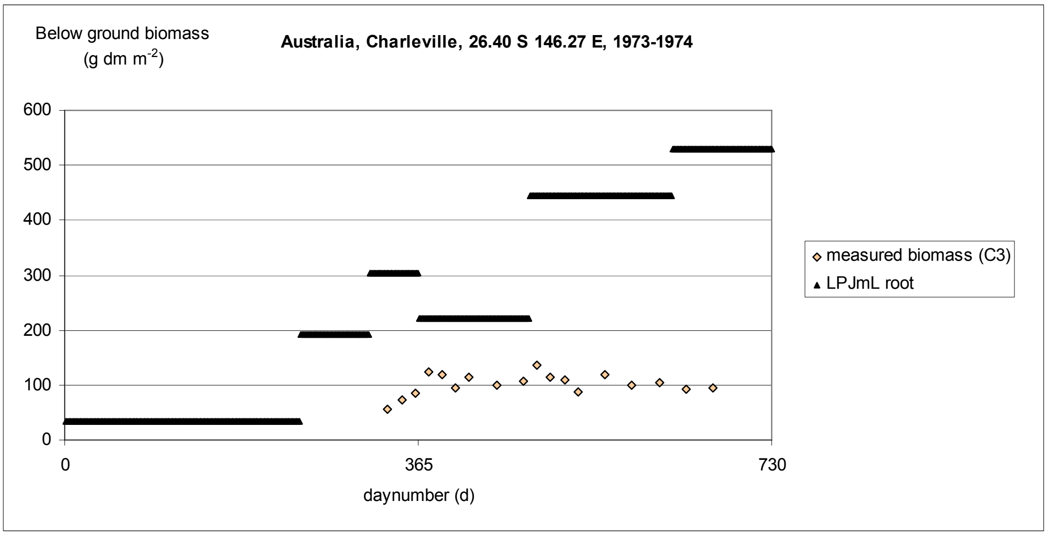


Figure 82 Measured and calculated belowground biomass in living roots.

5.1.5 North America (prairie)

5.1.5.1 North America, Colorado

Description

Productivity of a shortgrass prairie steppe was monitored at the Central Plains Experimental Range (CPER), sometimes referred to as the Pawnee Grassland study site, from 1939 to the present. Measurements of monthly dynamics of aboveground live biomass and dead matter were made from 1970 to 1975, for untreated and treated plots with irrigation, fertilization, and both irrigation and fertilization together (the "ESA" experiment). Further detailed data on live biomass, standing dead matter and litter will be made available later for four grazing treatments from 1970 to 1972, when total belowground biomass was also sampled (the "IBP" experiment).

The latter data were collected as part of a coordinated study over 1–3 years at ten grassland sites of the central and western United States, under the U.S. Grassland Biome Project of the International Biological Program (IBP). Since 1982, field research on the 6300-hectare CPER site has continued under the Shortgrass Steppe (SGS) Long-Term Ecological Research (LTER) project. The SGS LTER site was extended in 1996 to include the adjoining 78,000-hectare Pawnee National Grassland.

Estimates of annual aboveground net primary production (NPP) are available from 1939 to 1990, based on long-term data on annual forage production measured at the end of each growing season. Above and belowground NPP estimates, using (1) biomass increment methods and (2) 14-C turnover methods, will be available later for 1985–88. Data on vegetation and soil dynamics at CPER were used in the development of the CENTURY plant/soil organic matter model.

The CPER/SGS study site (40.82 N 104.77 W) is situated near the town of Nunn in northern Colorado, about 110 km north of Denver. The Pawnee National Grassland extends discontinuously for 90 km to the East. The shortgrass prairie is typically grazed annually by domestic animals, and would have been grazed by wild buffalo prior to the mid-19th century. Some of the region has been converted to arable crops, and some has subsequently been restored to grassland under the U.S. Conservation Reserve Program (Uresk *at al.*, 1996).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1970 – 1975 for grid number 6174. The calculated and measured living aboveground biomass for the CPER site of North America is given (Figure 83). LPJmL overestimates the amount of biomass in the leaves.

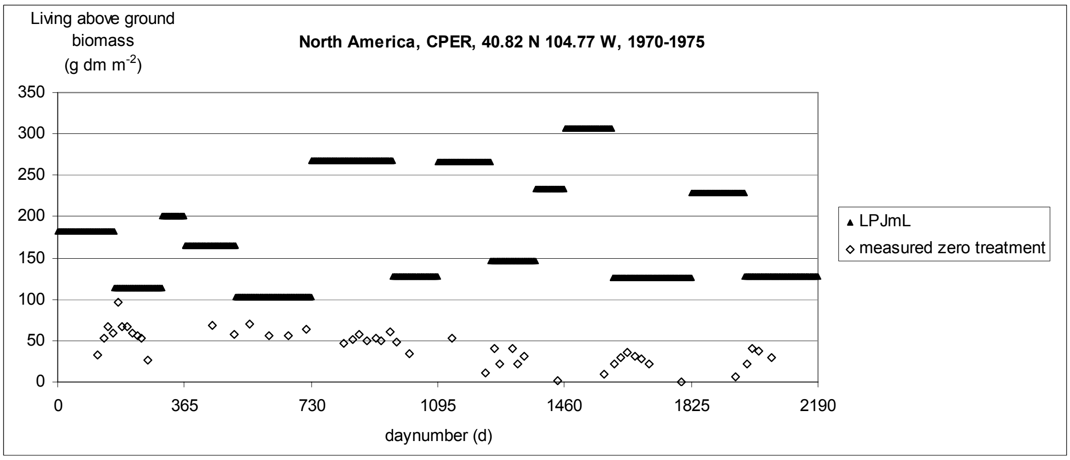


Figure 83 Measured and calculated aboveground biomass by LPJmL for the control treatment without fertilizer and irrigation at CPER 1970–1975 (g dm m^{-2}).

When irrigated the measured aboveground biomass production approaches the calculated values (Figure 84) of rainfed production.

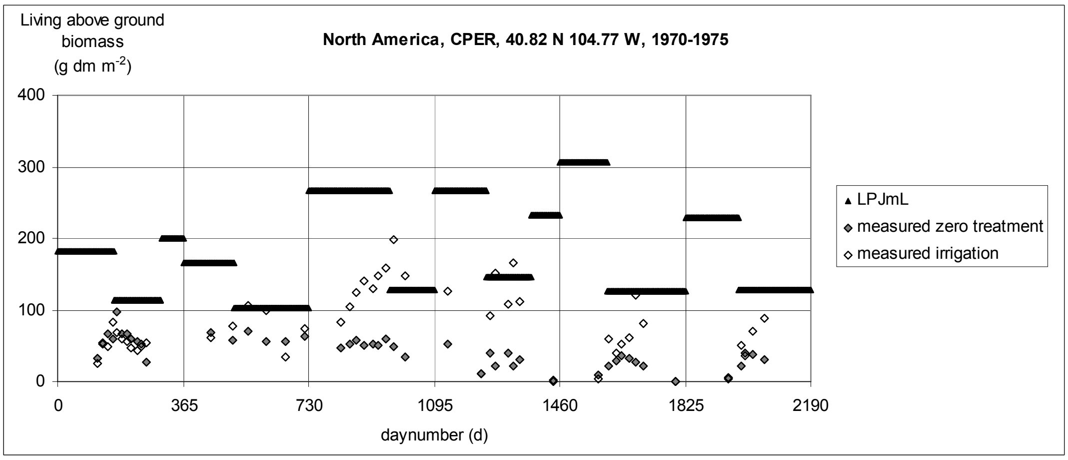


Figure 84 Measured and calculated amount of aboveground biomass by LPJmL for control and irrigated treatment at CPER 1970–1975 (g dm m^{-2}).

5.1.5.2 North America, Montana

Description

Productivity of mountain grassland was monitored at the Bridger study site in 1970 and 1972. Dynamics of aboveground plant biomass were monitored at roughly 2–week intervals during the growing season. Data on aboveground live biomass, standing dead matter and litter are available, for two replications of a grazed and an "ungrazed" (relatively undisturbed) treatment. Aboveground net primary production (ANPP) was estimated conservatively, by summing peak biomass of individual species, and belowground net primary production (BNPP) estimated as the sum of positive increments in total root plus crown biomass.

Data were collected as part of a coordinated study over 1–3 years at ten grassland sites of the central and western United States, under the U.S. Grassland Biome Project of the International Biological Program (IBP).

The Bridger study site (45.78 N 110.78 W) is situated at the U.S. Forest Service Bangtail Ridge Ranger Station in the Rocky Mountains, 22 km northeast of the city of Bozeman, Montana. The ungrazed treatment area had been protected from grazing since 1930. The high mountain meadow is surrounded by forests dominated by *Abies lasiocarpa* and *Pinus contorta* (Weaver & Collins, 1998).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1970 – 1973 for grid number 4215. The calculated and measured aboveground living biomass for the Montana site of North America is given (Figure 85). The measurement of the amount of biomass in the leaves fits the calculations by LPJmL although in 1972 LPJmL growth is slower than measured.

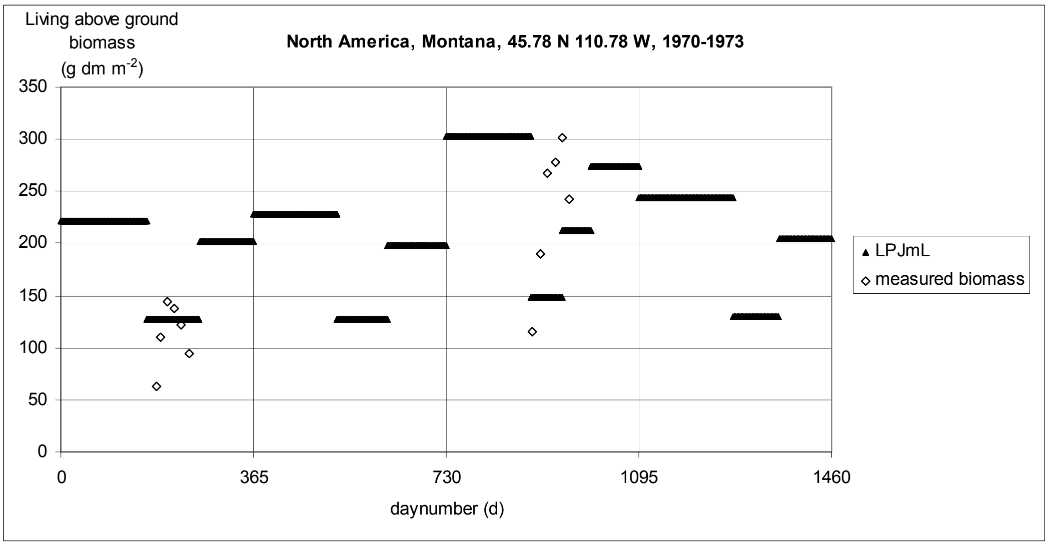


Figure 85 Measured and calculated aboveground biomass by LPJmL of the Bridger study site in Montana, North America, 1970–1973 (g dm m^{-2}).

5.1.5.3 North America, New Mexico

Description

Productivity of desert grassland was monitored at the Jornada IBP study site from 1970 to 1972. Dynamics of aboveground plant biomass were monitored at roughly 2–week intervals during the growing season. Data on aboveground live biomass, standing dead matter and litter are available, for two replications of a grazed and an "ungrazed" (relatively undisturbed) treatment. Total belowground biomass was also sampled. Aboveground net primary production (ANPP) was estimated conservatively, by summing peak biomass of individual species, and belowground net primary production (BNPP) estimated as the sum of positive increments in total root plus crown biomass.

Data were collected as part of a coordinated study over 1–3 years at ten grassland sites of the central and western United States, under the U.S. Grassland Biome Project of the International Biological Program (IBP).

The Jornada study site (32.60 N 106.85 W) is situated in the Basin and Range geomorphic province at the northernmost extent of the Chihuahua Desert, near the city of Las Cruces, New Mexico, about 60 km north-west of El Paso, Texas. Climate is characterized by sunshine, wide diurnal temperature range, low humidity and extremely variable precipitation. About half the annual rainfall typically occurs in brief, local, but intense, convective thundershowers during July to September. Winter precipitation (derived from the Pacific Ocean) is more variable than summer, but is more effective in wetting the soil profile.

Over the past 100 years, various factors including over-grazing and fire suppression have resulted in large areas of former black grama grassland being replaced by shrubland communities dominated by creosote bush, mesquite and tarbush. This produces a patchy distribution of soil nutrients, with nutrient rich areas under shrub canopies and soil resources lost from adjacent inter-shrub spaces by wind and water erosion, although there appears to be little change in NPP.

Field research is continuing on a variety of habitat types under the Jornada Long-Term Ecological Research (LTER) project, within the 26,000-hectare New Mexico State University Research Center and the adjacent 78,000-hectare U.S. Department of Agriculture Jornada Experimental Range (where the Jornada IBP Grassland Biome site is actually located) (Pieper, 1998).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1970 – 1972 for grid number 5715. The calculated and measured aboveground living biomass for the New Mexico site of North America is given (Figure 86). The measurements of the amount of biomass in the leaves fits the calculations by LPJmL. Overestimation by LPJmL is expected to leave some space for production gain by management and pests and disease control. The amount of incremented biomass does not reach the threshold of 100 g C m^{-2} (222 g dm m^{-2}) and no harvest or allocation of biomass to leaves and roots takes place. According to the measurements, there should be enough aboveground biomass for at least one harvest in 1970 and 1972, so LPJmL seems to underestimate the aboveground production for these years.

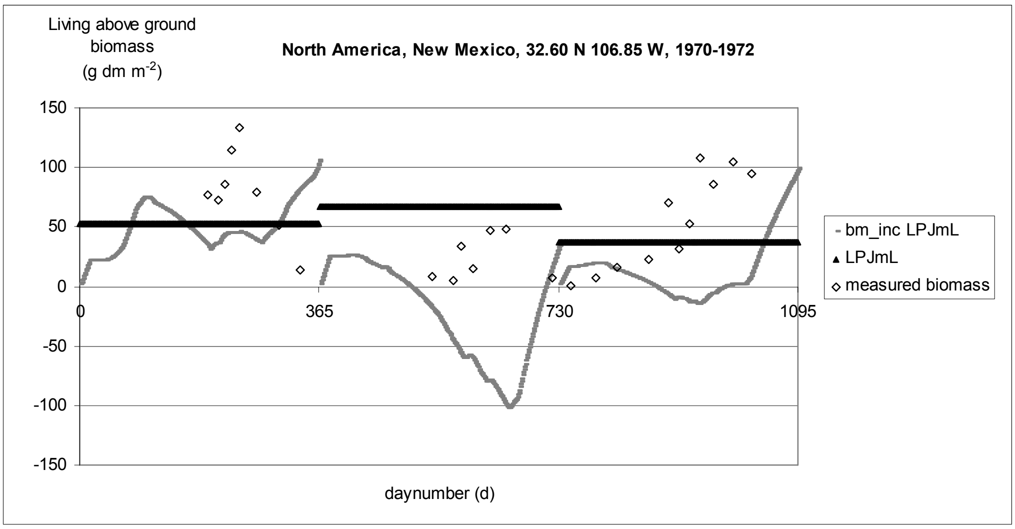


Figure 86 Measured, calculated living aboveground biomass and calculated accumulated biomass of the Jornada site in New Mexico, North America, 1970–1972 (g dm m^{-2}).

5.1.5.4 Canada, Saskatchewan

Description

Productivity of mixed prairie grassland was monitored at the Matador Field Station from 1968 through 1972. Monthly measurements of aboveground standing live and dead biomass and litter were made starting in either March or April and ending in October or November of each year. Root biomass was also measured. Untreated, burned, irrigated, fertilized, and grazed treatment areas were assessed for productivity, but only data for the untreated areas are included here.

This study was part of a total ecosystem study (the Matador Project), the objective of which was to measure energy flow of a grassland ecosystem by investigating its structure and function. As part of the International Biological Programme (IBP), the Matador Project was funded by the National Research Council of Canada and headquartered at the University of Saskatchewan. Other studies at the same site examined biomass and activity of all groups of flora, fauna and microorganisms, as well as abiotic factors that affect energy flow and nutrient cycling.

The 8 km^2 Matador Field Station (50.70 N 107.72 W) is located approximately 47 km north of the city of Swift Current in southern Saskatchewan Province, approximately 180 km SSW of Saskatoon, at the northern limit of the "mixed prairie" portion of the North American Great Plains. This area is in the bed of a former glacial lake, which has been cut by the South Saskatchewan River; the construction of a dam upstream has created Diefenbaker Lake immediately to the south. The principal study area for plant production, located within "Section 16", was 400 m x 60 m in size, and sampling took place within 4 m x 4 m subplots. A secondary study area ("Section 10") was initiated in 1970. The effect of grazing by cattle on the plot areas, which began in 1905 and was mostly limited to the winter months, was minimal or absent. Maximum leaf area index was reported as 1.5 in July 1970 and 1.0 in July 1971 (Coupland, 1999).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1968 – 1972 for grid number 5543. The calculated and measured aboveground living biomass for the Matador site of Canada is given (Figure 87). The calculated aboveground biomass of LPJmL has the expected overestimation of the measure amount of biomass in the leaves.

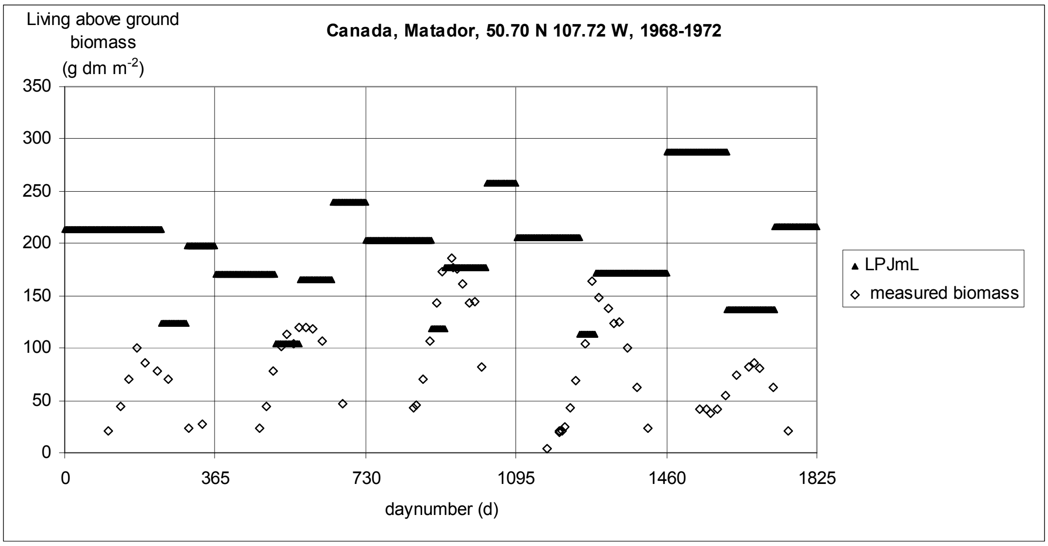


Figure 87 Measured and calculated living aboveground biomass of the Matador site in Saskatchewan, Canada, 1968–1972 (g dm m^{-2}).

5.1.6 Central America

5.1.6.1 Mexico, Montecillo

Description

Net primary production of saline grassland was determined at the Montecillo study site belonging to Colegio de Postgraduados, Texcoco, near Mexico City. Monthly dynamics of live biomass and dead matter, above and belowground, were monitored from 1984 to 1994, together with monthly litter bag estimates of decomposition rates above and belowground. The method for calculating net primary production accounted for simultaneous growth and death, and carbon flows to all trophic levels. Work was carried out under the United Nations Environment Program (UNEP) Project on "Primary Productivity of Grass Ecosystems of the Tropics" and has continued under subsequent international projects sponsored by UNEP and UK-ODA (Overseas Development Administration) sponsored international projects.

The study site of 1.5 hectares is situated on the northwest side of the Colegio's Montecillo campus and experimental fields (19.46 N 98.91 W), about 30 km east of Mexico City and 5 km southwest of Texcoco. The area is an old salt lakebed drained in 1911 and subsequently used for cattle grazing.

Net primary productivity was determined, initially under the auspices of an international collaborative UNEP Project, since there was a lack of information on the productive capacity and carbon cycling of the region. Complete data are available for the period 1984–1994, including burned and unburned plots, and comprise probably one of the most continuous detailed data sets for any grassland worldwide (Garcia-Moya, 1996).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1984 – 1994 for grid number 7514. The calculated and measured total accumulated living biomass for the Montecillo site of Mexico is given (Figure 88). The calculated total biomass of LPJmL overestimates the measured values. The calculated aboveground biomass by LPJmL matches the measured aboveground biomass (Figure 89) however, in 1984, 1985, 1990 and 1994 LPJmL is later than the measurements. The calculated belowground biomass by LPJmL matches the measured belowground biomass (Figure 90).

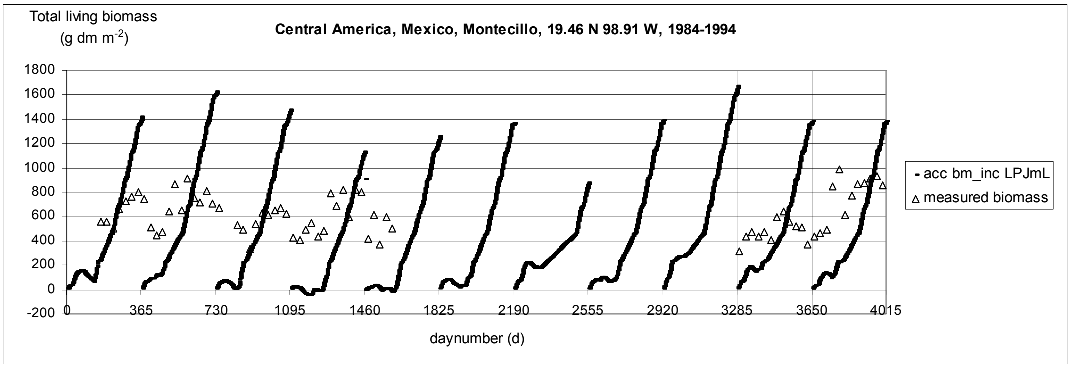


Figure 88 Measured and calculated total biomass by LPJmL for Mexico, Montecillo, 1984–1994 (g dm m^{-2}).

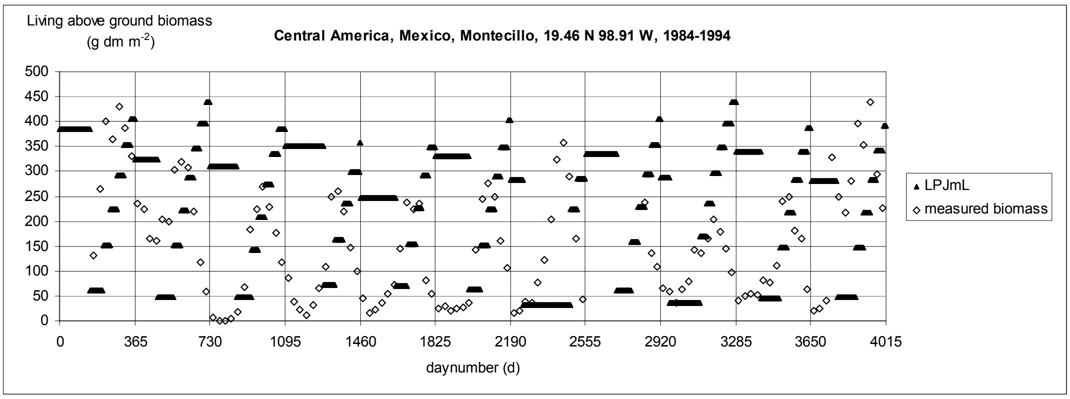


Figure 89 Measured and calculated aboveground biomass in Montecillo, Mexico from 1984 – 1994 (g dm m^{-2}).

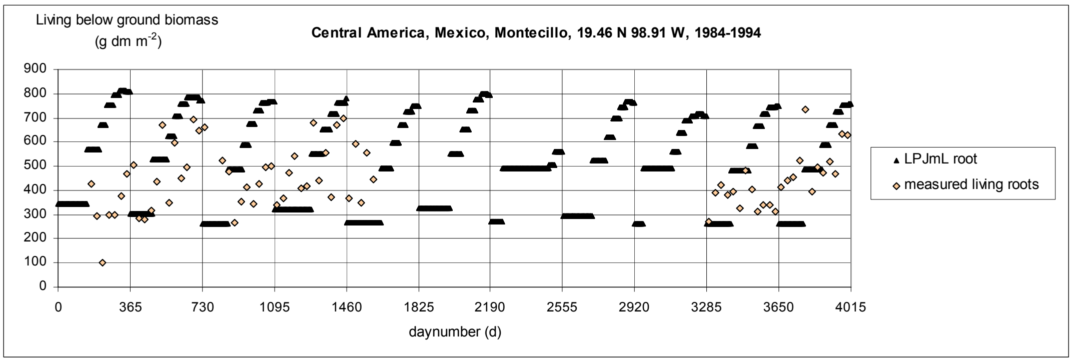


Figure 90 Measured and calculated belowground biomass by LPJmL for Mexico, Montecillo, 1984–1994 (g dm m^{-2}).

5.1.6.2 Venezuela, Calabozo

Description

Productivity of humid savanna was determined at the Estacion Biologica de Los Llanos, Calabozo, beginning in 1969. Much of the research work at this site has been carried out by staff from, or in association with, the Ecology Centre of the Venezuelan Institute for Scientific Research (Centro de Ecologia, Instituto Venezolano de Investigaciones Cientificas - IVIC).

The Calabozo study site (8.93 N 67.42 W) is situated 10 km south-southeast of Calabozo, Guarico State. It is typical of the Central Eastern Orinoco llanos of Venezuela, which occupy 300,000–500,000 km^2 of the grassy plains of northern South America. The llanos have been used for cattle grazing for at least the past 100 years, although forage production is modest and forage quality is poor (low in nutrients). The 260-hectare Calabozo study site has been protected from grazing and burning since 1960.

Monthly data on aboveground live biomass and total dead matter, and a single estimate of total belowground matter, are available for 1969. Burned and unburned plots were measured, as well as the effect of irrigation during the dry season. Note that data have been read from published graphs; therefore, the least significant digit may be in error. Total NPP (above and belowground) was estimated at 682 g m^{-2} yr^{-1} for unburned and 755 g m^{-2} for burned plots, although later estimates range from 365 to 968 g m^{-2} yr^{-1} (40–50% of production belowground) (San Jose & Montes, 1998).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1968 – 1970 and 1985 – 1988 for grid number 15545. In Figure 91 and Figure 92 the calculated and measured aboveground living biomass for Venezuela in 1968–1970 and 1985–1988 is given. LPJmL calculates an expected overestimation of the amount of living aboveground biomass. The increase of biomass of measured and calculated biomass matches but the measured data seems to develop earlier.

Figure 93 and Figure 94 indicate a strong influence of the precipitation on the leaf growth. The onset of the rain is the starting point for grass growth.

When the increment of biomass is taken into account (Figure 95 and Figure 96), the biomass growth calculated by LPJmL coincides with the measured aboveground biomass in Venezuela. Biomass increment seems faster than the measured data but biomass increment is total biomass so part of it has to be allocated to the roots. This will delay the leaf growth.

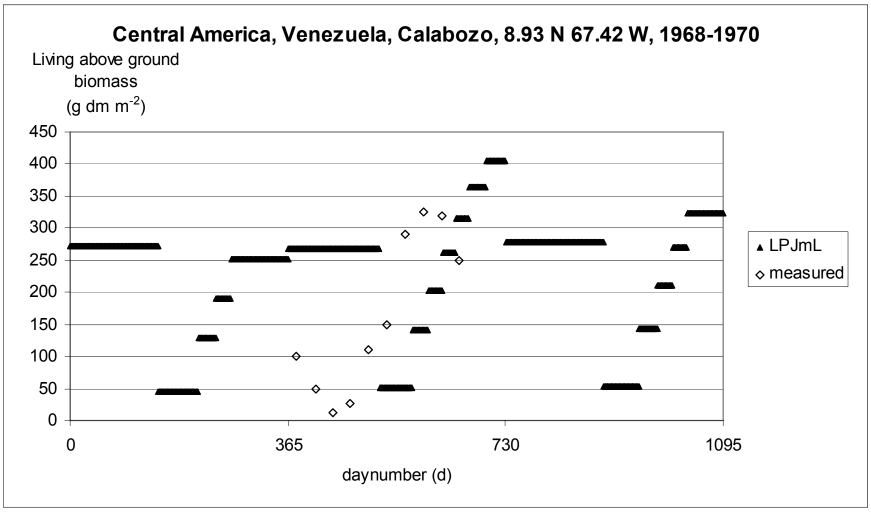


Figure 91 Measured and calculated living aboveground biomass of the Calabozo site in Venezuela, 1968–1970 (g dm m^{-2}).

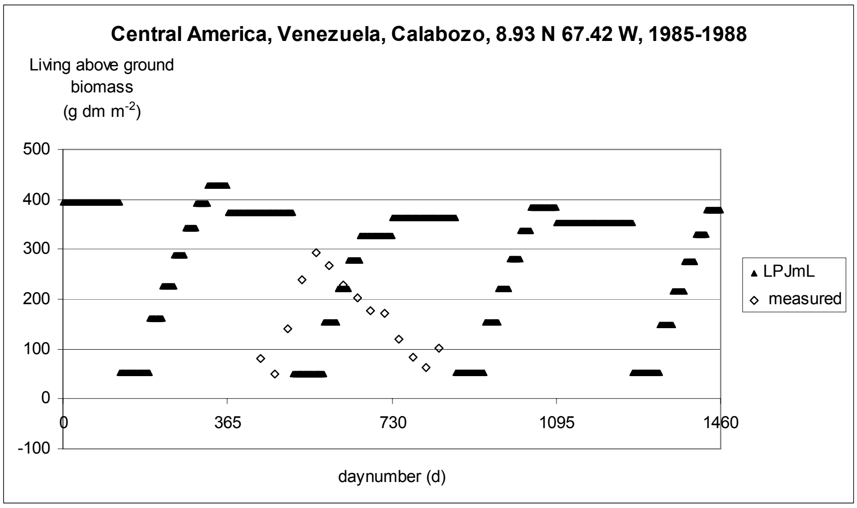


Figure 92 Measured and calculated aboveground biomass of the Calabozo site in Venezuela, 1985–1988 (g dm m^{-2}).

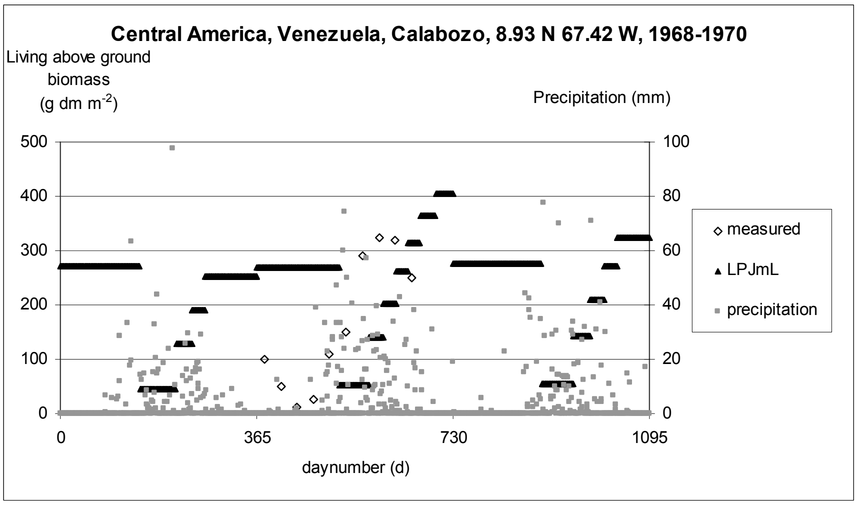


Figure 93 Measured and calculated aboveground biomass and daily precipitation (calculated by LPJmL) of the Calabozo site in Venezuela, 1968–1970.

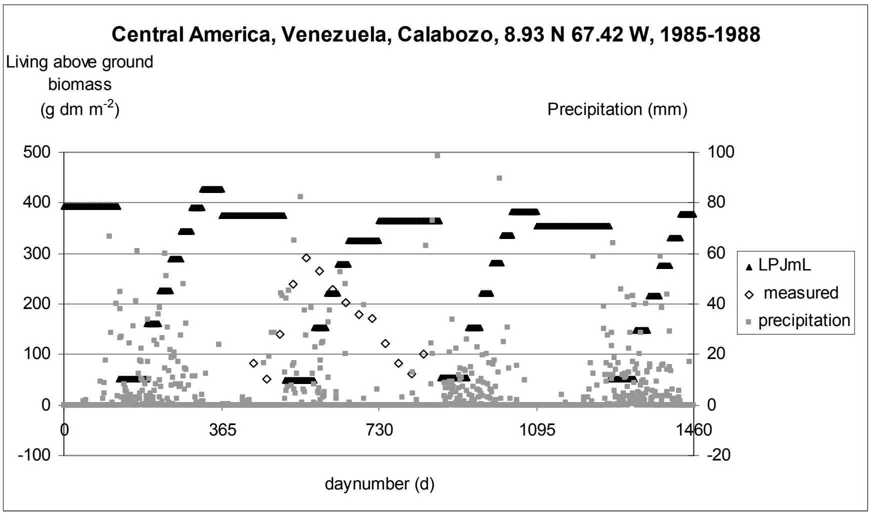


Figure 94 Measured and calculated aboveground biomass and precipitation (calculated by LPJmL) of the Calabozo site in Venezuela, 1985–1988.

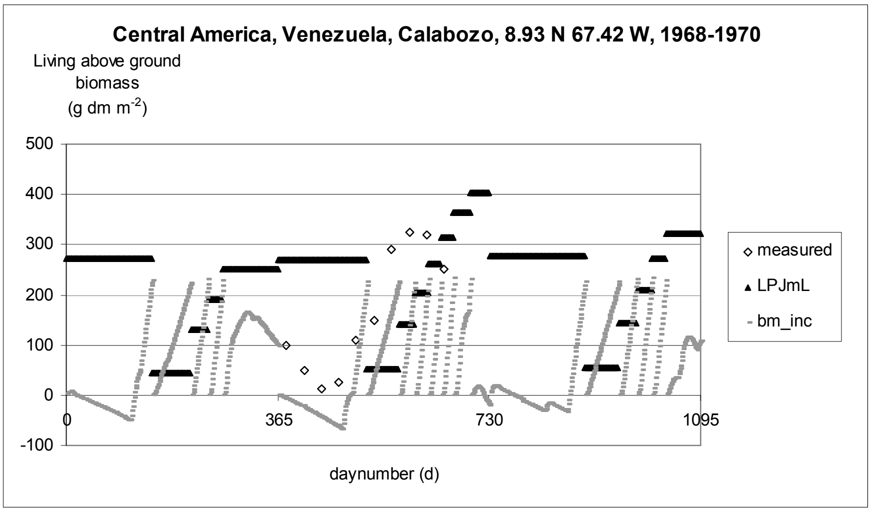


Figure 95 Measured and calculated aboveground biomass and biomass increment (calculated by LPJmL) of the Calabozo site in Venezuela, 1968–1970.

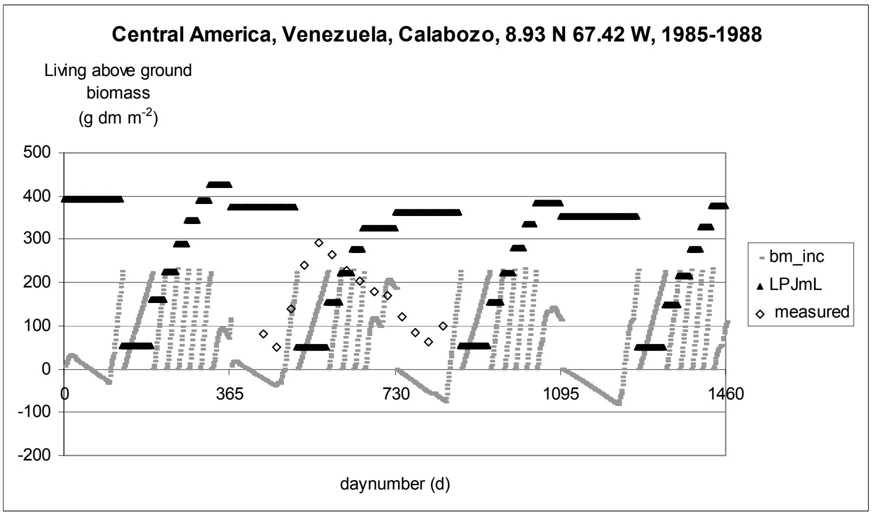


Figure 96 Measured and calculated aboveground biomass and biomass increment (calculated by LPJmL) of the Calabozo site in Venezuela, 1985–1988.

5.1.7 South America (pampas)

5.1.7.1 Argentina, Media Luna

Description

Productivity of a temperate grassland steppe was studied at the Media Luna Ranch in Patagonia, Argentina, during 1981–1983. Dynamics of aboveground biomass, dead matter and litter were monitored at monthly or bi-monthly intervals, but NPP was not estimated.

The study site was a 2.5 hectare enclosure at the Media Luna Ranch (45.60 S 71.42 W), situated on the Rio Mayo terraces and representative of one of the most important grassland areas of Patagonia, a narrow belt in the foothills of the Andes. The area is characterized by a cold wet winter and a warm dry summer, with a growing season extending from September to April, interrupted by a mid-summer drought. The region has been over-grazed by introduced livestock since the early 1900s, and is currently used for sheep production.

Bi-monthly data on aboveground live biomass (95% of which is accounted for by the dominant grass species, Festuca pallescens (St. Yves) Parodi (C3)), together with recent standing dead matter (yellow), old standing dead (grey) and litter, are available for two growing seasons from 1981 to 1983 (N.B.: Southern Hemisphere growing seasons) (Defosse & Bertiller, 1998).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1981 – 1983 for grid number 13860. In Figure 97 the calculated and measured aboveground living biomass for Argentina, the Media Luna site in 1981 and 1983 is given. The measured and calculated aboveground biomass coincides; there is no overestimation by LPJmL.

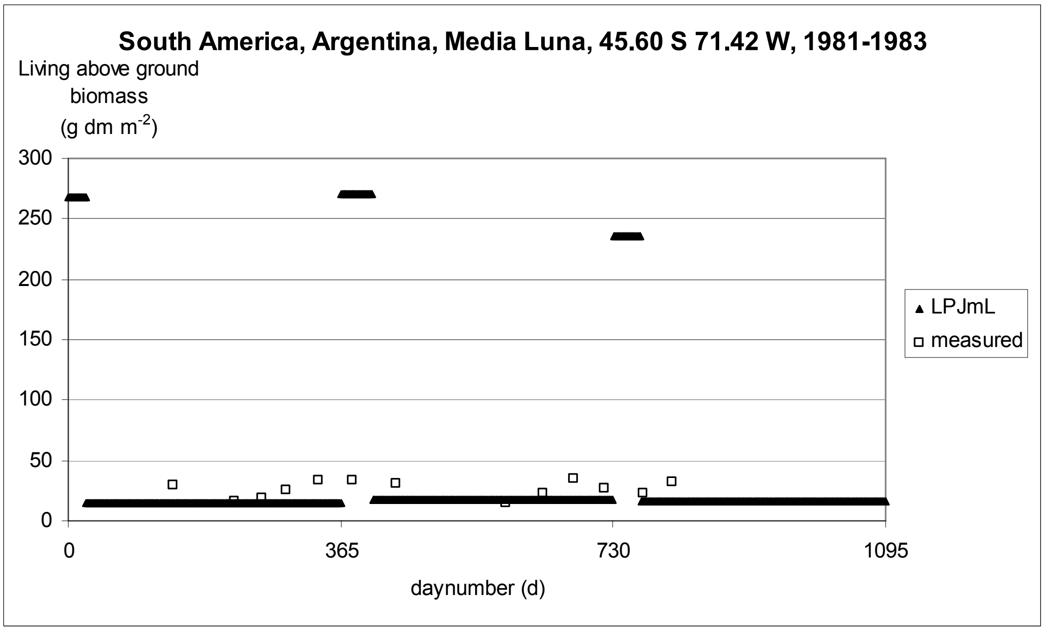


Figure 97 Measured and calculated living aboveground biomass in Media Luna, Argentina from 1981 – 1983 (g dm m^{-2}).

5.1.7.2 Argentina, Pampa de Leman

Description

Productivity of a dwarf-shrub steppe was studied at the Pampa de Leman site, Estancia Külper, in Chubut (Northern Patagonia), Argentina, during 1980–1982 (Figure 98). Dynamics of aboveground biomass, dead matter and litter were monitored at monthly or bi-monthly intervals, and NPP was estimated.

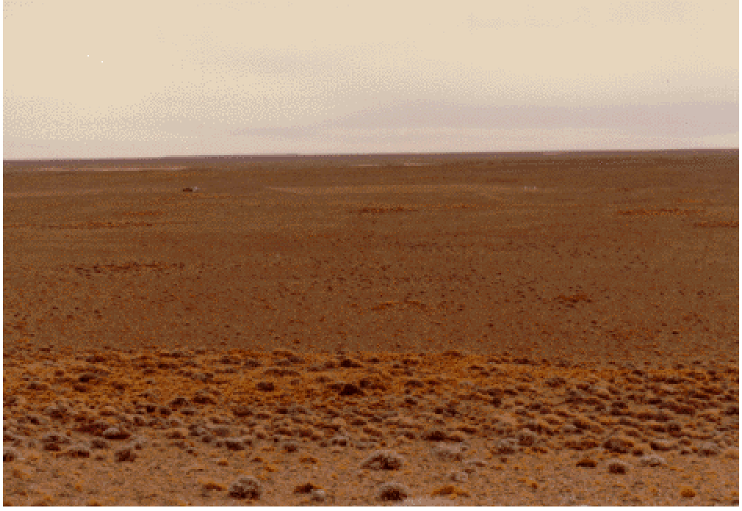


Figure 98 General view of the study area near the Pampa de Leman site, Argentina, looking from Northeast to South-West. (Photograph taken 6th August 1982 by Dr. M.B. Bertiller, Centro Nacional Patagonico, Argentina).

An area of 1.5 hectares was protected from sheep grazing at the study site, comprising a community of prostrate vegetation with low ground cover (10–20%), dominated by the dwarf shrub *Nassauvia glomerulosa*, with two grasses (*Poa dusenii* and *Hordeum comosum*) (Figure 99). The Pampa de Leman site was located on an alluvial terrace of the Senguerr river (45.43 S 69.83 W), in an arid region characterized by continental dry westerly winds which tend to produce soil erosion.

Figure 99 Close-up view of the Pampa de Leman study site, Argentina. (Grazed area in the foreground; enclosure where the study was carried out in the background. Photograph taken 6 August 1982 by Dr. M.B. Bertiller, Centro Nacional Patagonico, Argentina).

Erosion was exacerbated by the introduction of domestic sheep to the area around 1900, upsetting the equilibrium, which previously existed between vegetation and native herbivores. Monthly/bi-monthly data on aboveground live biomass (>90% of which is accounted for by the dominant shrub species), together with recent standing dead matter (yellow), standing dead (grey) and litter, are available for two growing seasons from 1980 to 1982 (N.B.: Southern Hemisphere growing seasons). However, climate data for this site are limited to measurements made for the duration of the study (Bertiller, 1998).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1980 – 1982 for grid number 14460. In Figure 100 the calculated and measured aboveground living biomass for Argentina, the Pampa de Leman site in 1980 and 1982 is given. After the second harvest, LPJmL overestimates the measured data.

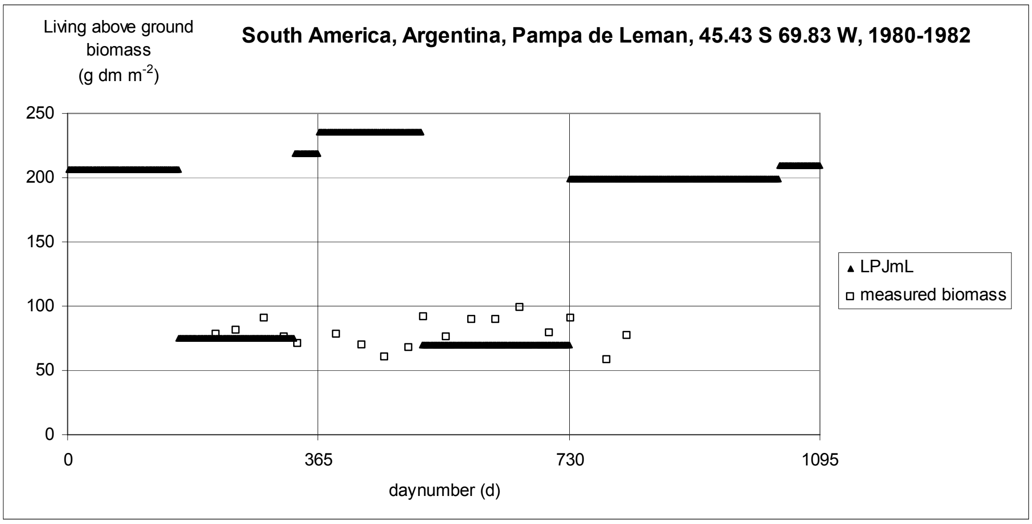


Figure 100 Measured and calculated living aboveground biomass for Pampa de Leman, Argentina from 1980 – 1982 (g dm m^{-2}).

5.1.8 Europe

5.1.8.1 Kazakhstan, Dzhanybek

Description

Productivity of a semi-desert steppe was determined at the Dzhanybek Research Station in Kazakhstan, between 1955 and 1989. These data are part of a series of grassland data sets recently assembled and checked by Dr. Tagir Gilmanov. These data sets cover a wide range of climate and "continentally" (increasing maximum summer temperatures, decreasing precipitation) from the North- West to the Southeast of the Commonwealth of Independent States (former U.S.S.R.).

The Dzhanybek study site (49.33 N 46.78 E) is situated across the Russia/Kazakh border from Volgograd, located on the Caspian Sea Lowlands.

A long time series of peak live biomass measurements are available from 1955 to 1989 (excluding 1976). Detailed data on the seasonal dynamics of aboveground living biomass and dead matter are available for 1985–1989 (Gilmanov, 1997).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1955 – 1989 for grid number 40703. In Figure 101 the calculated and measured aboveground living biomass for Kazakhstan, the Dzhanybek site for 1955 and 1989 is given. The measured and calculated aboveground biomass coincides, with a little overestimation by LPJmL.

In Figure 102 the increase in biomass calculated by LPJmL (black line) matches the measured aboveground biomass (white squares) however; LPJmL growth starts 43 and 49 days later in 1986 and 1988 resp.

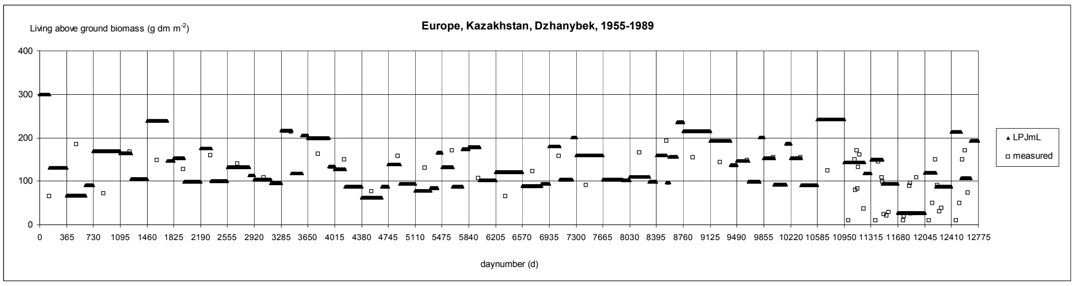


Figure 101 Measured and calculated living aboveground biomass in Dzhanybek, Kazakhstan from 1955 – 1989 (g dm m^{-2}).

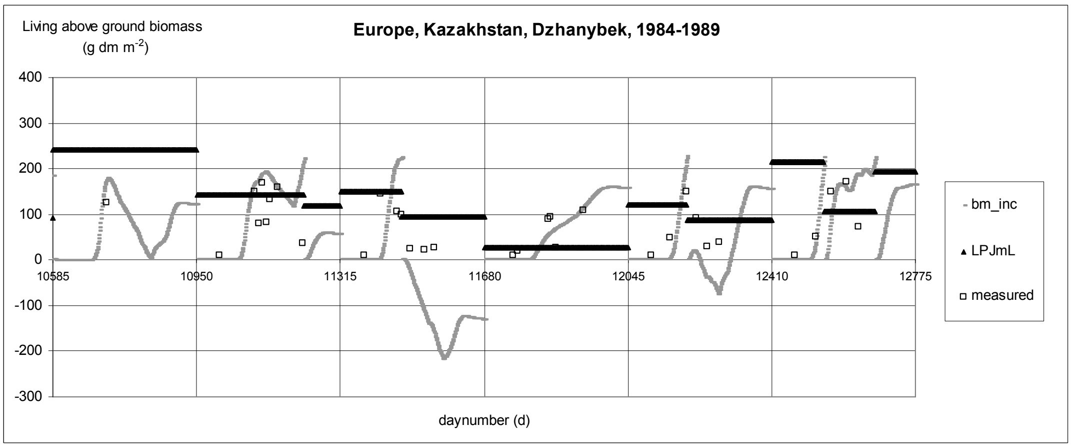


Figure 102 Measured and calculated living aboveground biomass and biomass increment in Dzhanybek, Kazakhstan for 1984 – 1989 (g dm m^{-2}).

5.1.8.2 Kazakhstan, Shortandy

Description

Productivity of a dry steppe was determined at the Shortandy study site from 1975 to 1980. Measurement of monthly dynamics of above- and belowground live biomass and dead matter were made for each growing season (April-September). Cumulative aboveground net primary production was estimated. These data are part of a series of grassland data sets recently assembled and checked by Dr. Tagir Gilmanov, which cover a wide range of climate and "continentally" across the Commonwealth of Independent States (former U.S.S.R.).

The Shortandy study site (51.7 N 71.0 E) is situated near the city of Astana (former names Aqmola/Akmolinsk/ Tselinograd). This kind of steppe was typically grazed annually before about 1900, although the study site itself is not grazed. It represents one of the last few square kilometers of "virgin" typical dry steppe in northern Kazakhstan, in an area largely converted to wheat production in the 1950s. The remnant virgin steppe is thought to be in good condition, with large amounts of carbon stored in its soil.

Data on growing season dynamics of aboveground biomass, dead matter and litter, belowground live biomass and dead matter are available for three years, 1977–1980. In addition, data exist for a single measurement of peak above and belowground matter in 1978 (Gilmanov, 1996a).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1977 – 1980 for grid number 45841. In Figure 103, the calculated and measured aboveground living biomass for Kazakhstan, the Shortandy site from 1977 to 1980 is given. The calculated biomass by LPJmL overestimates the measured data.

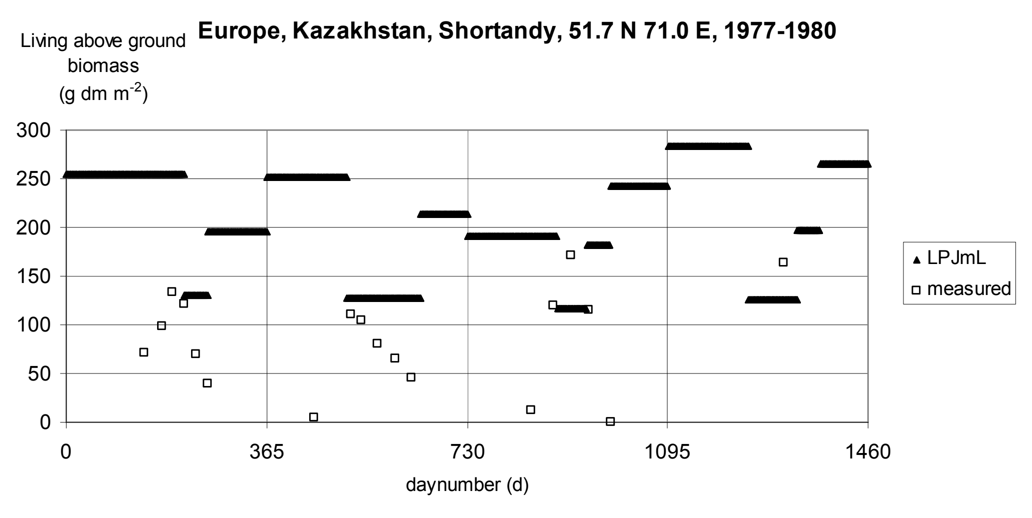


Figure 103 Measured and calculated living aboveground biomass for Shortandy, Kazakhstan from 1977 – 1980 (g dm m^{-2}).

5.1.8.3 Russia, Kursk

Description

Productivity of a meadow steppe was determined at the Kursk long-term ecological study site from 1954 to 1983. Measurement of monthly dynamics of aboveground plant biomass were made for each growing season (April-October), although the data on live and dead matter are more sparse and root data collection covers only some years in the 1970s and 1980s. Aboveground net primary production was estimated for many years, but the record is discontinuous. These data are part of a series of grassland data sets recently assembled and checked by Dr. Tagir Gilmanov. These data sets cover a wide range of climate and "continentally" (increasing maximum summer temperatures, decreasing precipitation) from the North-West to the South- East of the Commonwealth of Independent States (former U.S.S.R.). The Kursk study site (51.67 N 36.5 E) is situated close to the city of Kursk in eastern Russia, 500 km south of Moscow. This kind of meadow is typically mowed annually.

A long time series of aboveground biomass data is available for each growing season from 1954 to 1983. There is also a discontinuous record of aboveground biomass, dead matter and litter from 1956 to 1983, as well as root data for 1972–1973 and 1981–1983 (Gilmanov, 1996d).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1954 – 1983 for grid number 14460. The total accumulated biomass production of LPJmL is compared with the sum of living above and belowground measured biomass (Figure 104). The calculated total accumulated biomass by LPJmL is underestimated.

In Figure 105 the calculated and measured aboveground living biomass for Russia, Kursk for 1954 to 1983 is given. LPJmL calculations underestimates in 19 of the 30 years, the onset of calculated and measured biomass growth matches but the growth rate of the calculated aboveground biomass is slower than the measured growth rate.

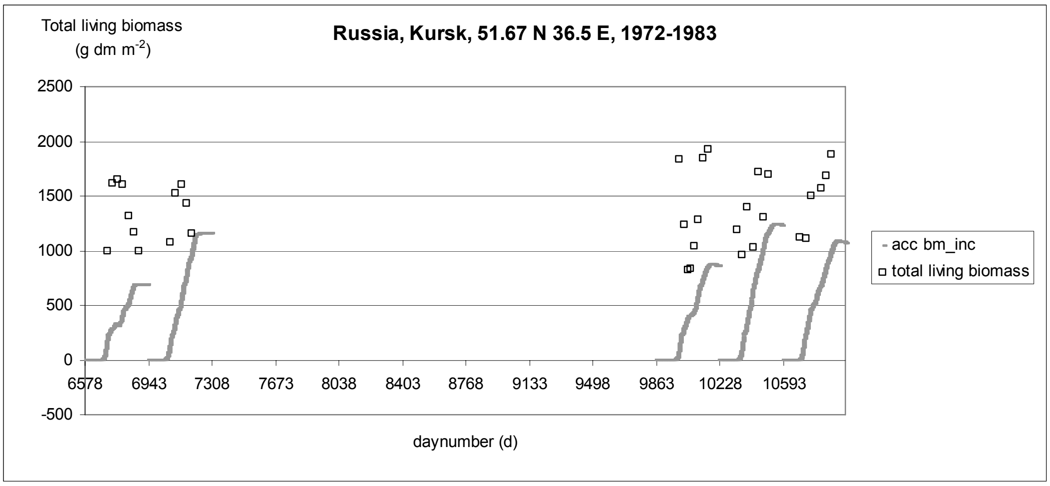


Figure 104 Measured and calculated total living biomass by LPJmL (without standing dead matter and litter or dead roots) for Russia, Kursk, for 1972 to 1983 (g dm m^{-2}).

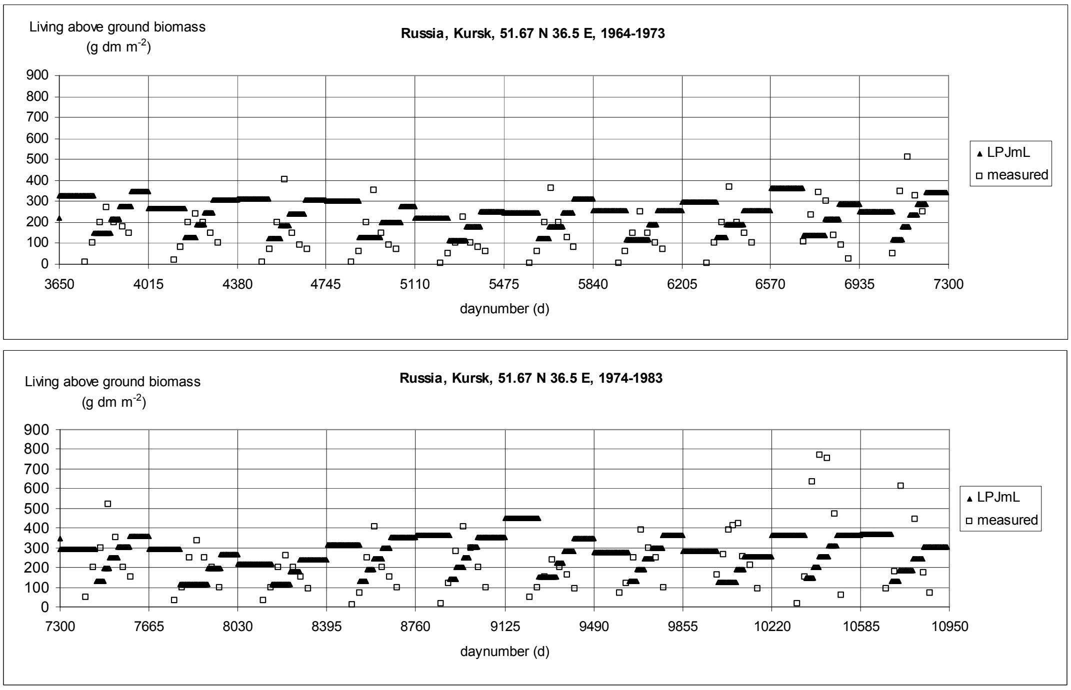


Figure 105 Measured and calculated living aboveground biomass in Kursk, Russia from 1954 – 1983 (g dm m^{-2}).

In Figure 106 the measured belowground biomass is compared with calculated LPJmL results for four years. The amount of biomass to the roots is underestimated by LPJmL and the shape of the curve is different. In LPJmL, the amount of underground biomass continues to increase until the end of the year, where the amount of measures underground biomass increases until the middle of the year and decreases towards the end of the year.

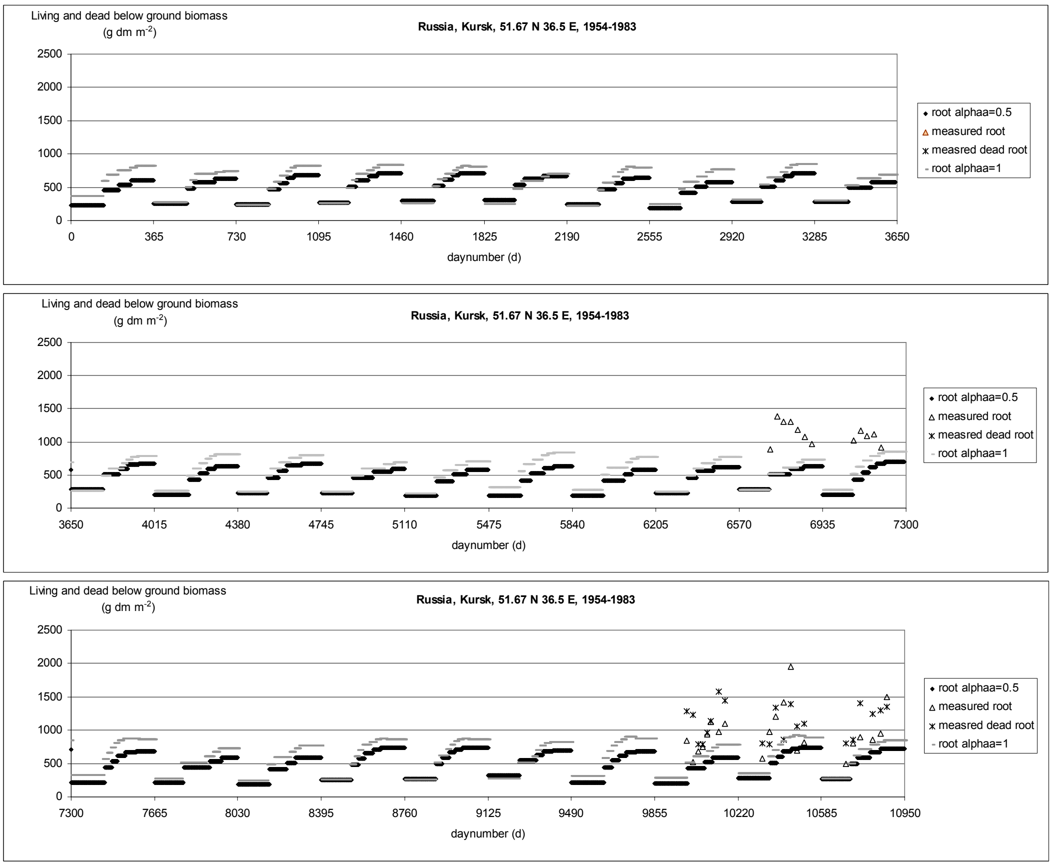


Figure 106 Calculated amount of biomass of living roots by LPJmL and measured belowground biomass (without dead roots) for Russia, Kursk from 1954–1983 (g dm m^{-2}).

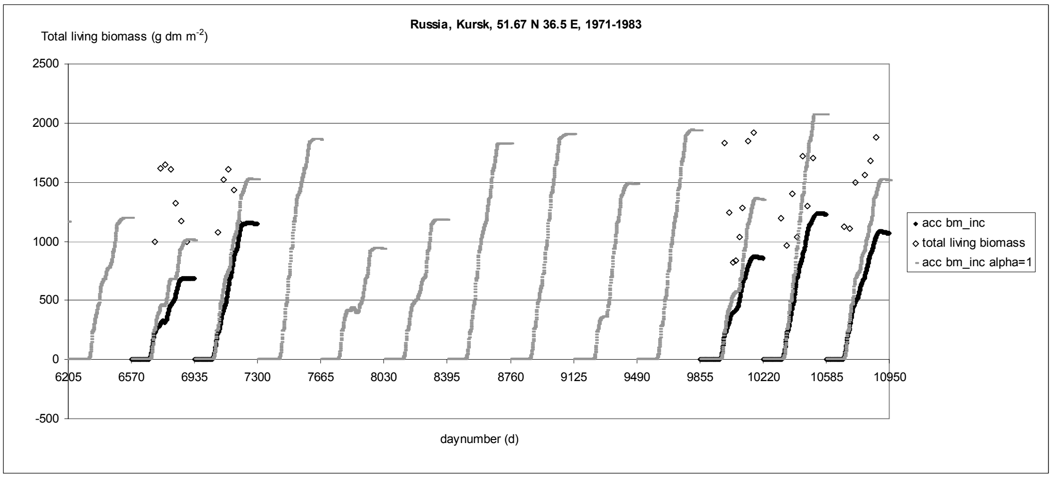


Figure 107 Measured and calculated total living biomass and biomass increment (calculated by LPJmL) with ecosystem parameter alpha$_a$ set to 0.5 (black) and 1 (gray lines).

LPJmL underestimates the total amount of biomass. A reason for this may be the management factor alpha$_a$ (see section 4.3.1). Results for total biomass, above and belowground biomass with of the elimination of this factor (set to 1) are given in Figure 107, Figure 108 and Figure 109.

The calculated total amount of biomass increased, because of the value change of alpha$_a$ to one. However, Figure 107 still shows an underestimation of the total biomass for three out of five years. The amount of root biomass has increased (Figure 109), but is still too low and the amount of biomass in the leaves has increased and started a little earlier (Figure 108) but the calculations are still too low and continuation of leaf biomass growth is still too slow.

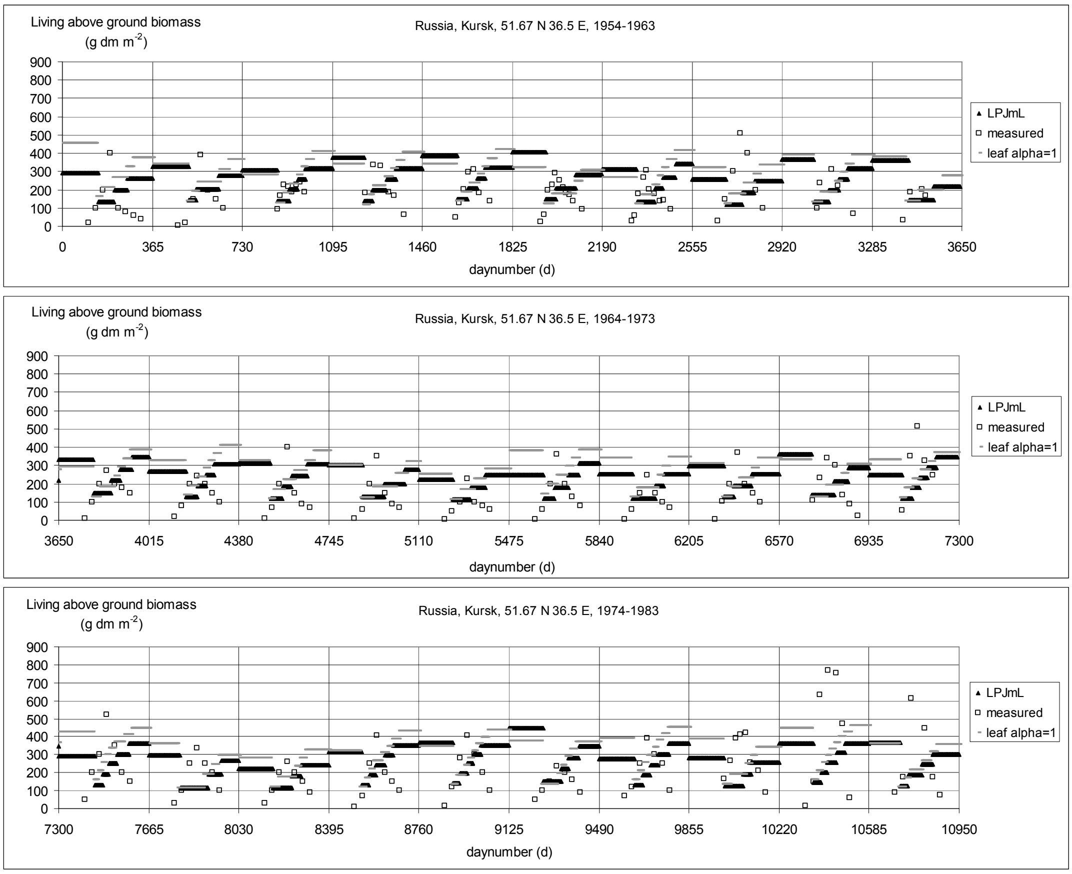


Figure 108 Measured and calculated living aboveground biomass (calculated by LPJmL) with ecosystem parameter alpha$_a$ set to 0.5 (black triangle) and 1 (gray lines).

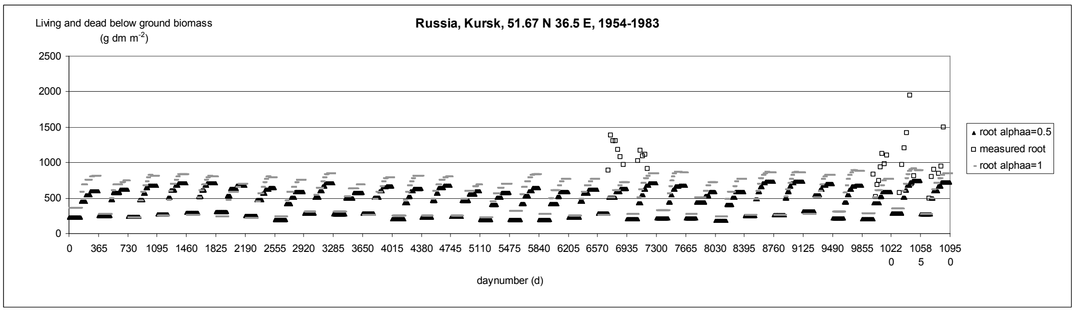


Figure 109 Measured and calculated living belowground biomass (calculated by LPJmL) with ecosystem parameter alpha$_a$ set to 0.5 (black triangles) and 1 (gray lines).

In Figure 110 the accumulated biomass is added to the third part of Figure 105. The growth rate of accumulated biomass is the same as the growth rate of the measured aboveground biomass.

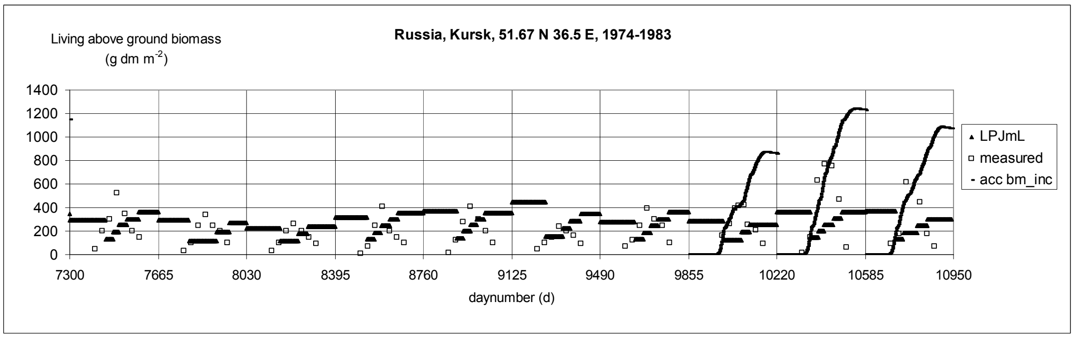


Figure 110 Measured and calculated living aboveground biomass (calculated by LPJmL) and total accumulated biomass.

5.1.8.4 Russia, Otradnoe

Description

The productivities of two meadows (i.e., one loamy soil, one sandy soil) were determined at the Otradnoe study site from 1969 to 1973. Measurements of monthly dynamics of aboveground and belowground plant biomass were made for each growing season (April-October). Aboveground net primary production was estimated for each year. These data are part of a series of grassland data sets recently assembled and checked by Dr. Tagir Gilmanov, which cover a wide range of climate and "continentally" (increasing maximum summer temperatures, decreasing precipitation) from the North- West to the South-East of the Commonwealth of Independent States (former U.S.S.R.).

The Otradnoe study sites (60.8 N 30.3 E) are situated on the Karelian peninsula, 100 km north of St. Petersburg in northwestern Russia. They were established for the Russian International Biological Programme (IBP) by the V.L. Komarov Botanical Institute of the Russian Academy of Sciences. This kind of meadow represent man made pastures in the southern taiga sub-zone of the forest zone, and are typically mowed annually.

Monthly dynamics of above and belowground live and dead matter are available for the sandy meadow from 1969 to 1971, and for the loamy meadow from 1969 to 1972. There is also a single determination of above and belowground live and dead matter at the sandy meadow site for June 1972, and additionally a single determination of only aboveground live and dead matter at the loamy meadow site for May 1973. Monthly N, P, and S, content of aboveground live biomass are available for 1969–1971 at the sandy meadow site (Gilmanov, 1996c).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1969 – 1973 for grid number 35475. The total accumulated biomass production of LPJmL is compared with the sum of living above and belowground measured biomass (Figure 111). The calculated total accumulated biomass by LPJmL underestimates the measured values for sandy soil and matches the measured values for loamy soil. The onset of biomass growth by LPJmL is too late in comparison with the measured data.

The calculated aboveground biomass by LPJmL has the expected overestimation for three of the four years. The measured aboveground biomass for sandy soil is higher than the measured aboveground biomass for loamy soils; hence, the overestimation by LPJmL is higher for loamy soils (Figure 112). The calculated growth rate is less slow than the calculated growth rate of the total biomass but still too slow.

The value of calculated belowground biomass underestimates the measured amount of belowground biomass for a sandy soil and has de same level as the amount of belowground biomass for a loamy soil (Figure 113). The calculated growth rate of belowground biomass is too slow.

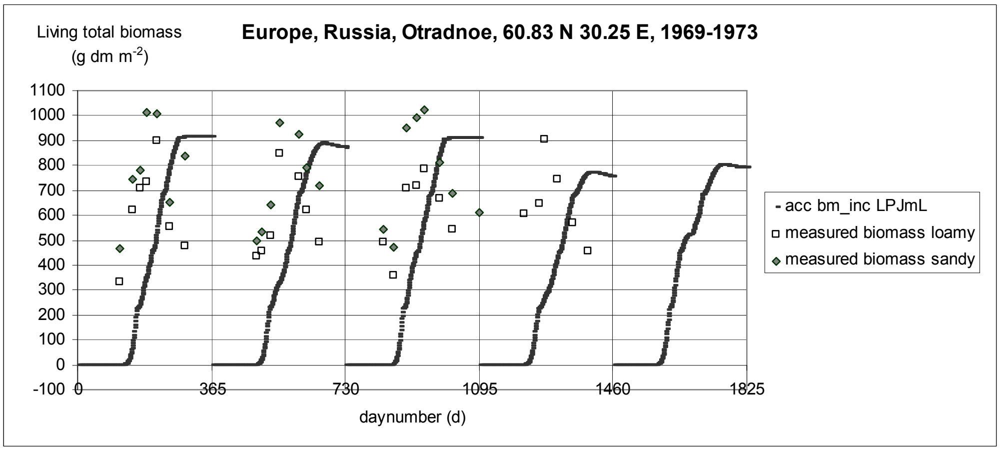


Figure 111 Measured (triangles) and calculated total living biomass (gray stripes) for Russia, Otradnoe from 1969–1973 on a loamy (open square) and sandy (gray diamonds) soil.

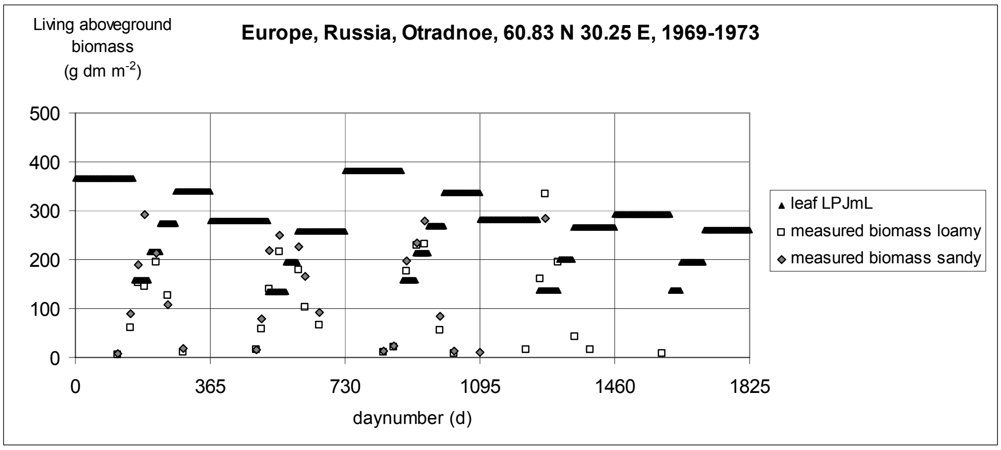


Figure 112 Measured and calculated living aboveground biomass for sandy and loamy soils in Otradnoe, Russia, from 1969 – 1973 (g dm m^{-2}).

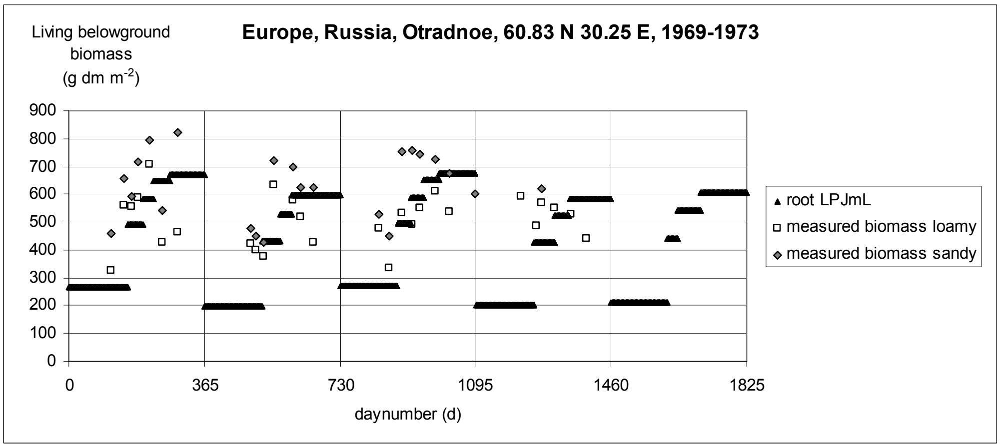


Figure 113 Measured and calculated living belowground biomass (calculated by LPJmL) for sandy and loamy soils in Otradnoe, Russia from 1969 – 1973 (g dm m^{-2}).

5.1.8.5 Russia, Tuva

Description

Productivity of an ultra-continental steppe was determined at the Tuva study site from 1978 to 1985. Measurements of monthly dynamics of aboveground plant biomass were made for each growing season (May-August). Cumulative aboveground net primary production was estimated for some years. These data are part of a series of grassland data sets recently assembled and checked by Dr. Tagir Gilmanov, which cover a wide range of climate and "continentally" across the Commonwealth of Independent States (former U.S.S.R.).

The Tuva study site (51.83 N 94.42 E) is situated near the city of Kyzyl, close to the geographical center of the Asian continent. This kind of steppe is typically grazed annually.
Data on growing season dynamics of aboveground biomass, dead matter and litter, and peak live root biomass are available for 1978–1980. Peak aboveground biomass, dead matter and litter are available for 1981–1985, as well as dynamics of aboveground live biomass for 1984–1985 and a single data point for the winter of 1980 (Gilmanov, 1996e).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1978 – 1985 for grid number 51269. The total accumulated biomass production of LPJmL is compared with the total living measured biomass (Figure 114). The calculated accumulated total biomass by LPJmL underestimates the measured values.

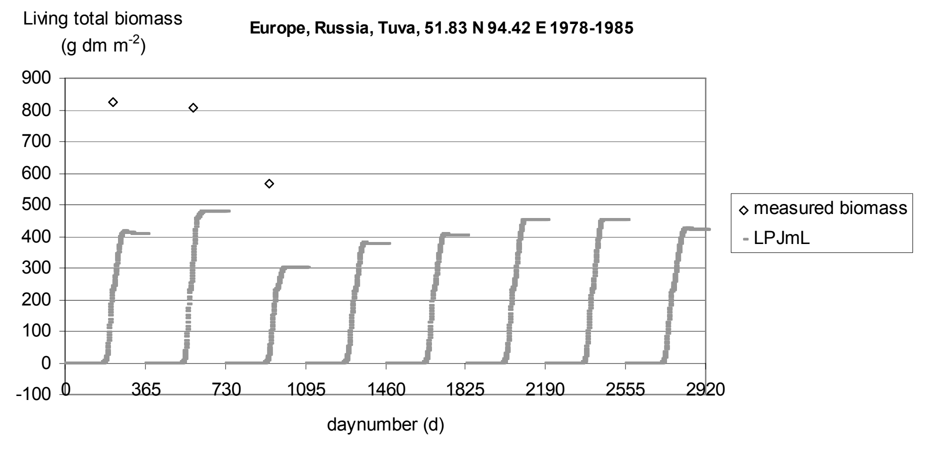


Figure 114 Measured (diamonds) and calculated incremented total living biomass (gray stripes) for Russia, Tuva from 1978–1985.

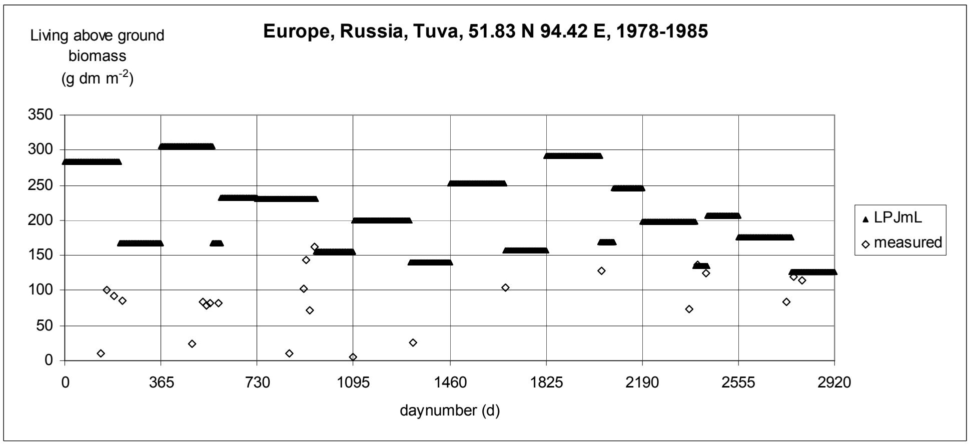


Figure 115 Measured and calculated living aboveground biomass in Tuva, Russia from 1978 – 1985 (g dm m^{-2}).

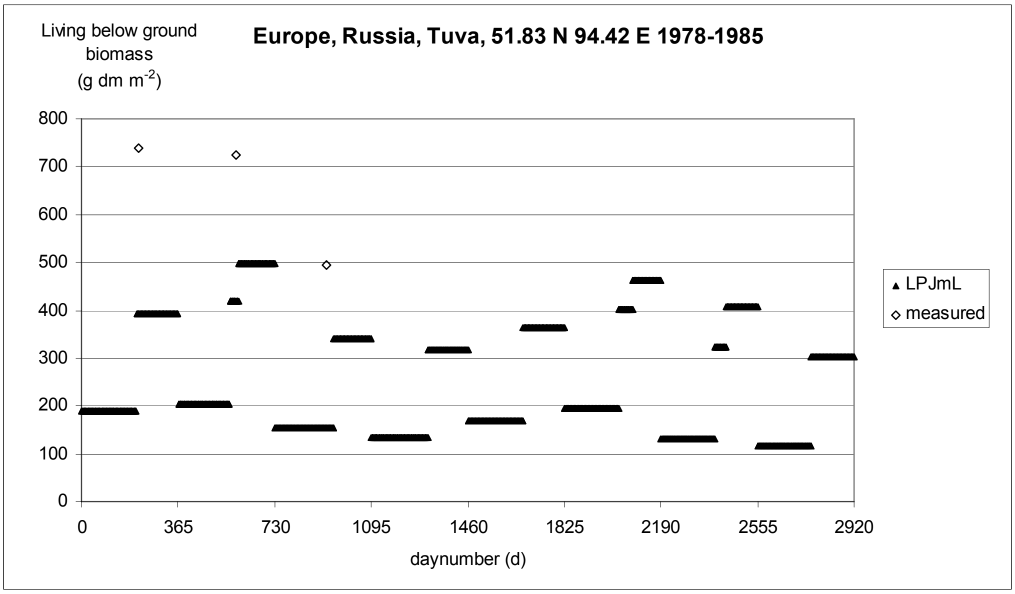


Figure 116 Measured and calculated living belowground biomass in Tuva, Russia from 1978 – 1985 (g dm m^{-2}).

The total amount of biomass is underestimated by LPJmL, the amount of biomass in the leaves is overestimated (Figure 115), hence the amount of biomass in the roots is underestimated (Figure 116). Because, an underestimation is expected for both above and belowground biomass, too much biomass must be allocated to the leaves on this location.

5.1.8.6 Ukraine, Khomutov

Description

Productivity of a "typical" steppe was determined at the Khomutovskaya Ukrainian Steppe Natural Reserve in Donezk Region, from 1967 to 1970. Measurements of monthly dynamics of aboveground plant biomass were made for each growing season (April-August/September). Cumulative aboveground net primary production was estimated for each year. These data are part of a series of a series of grassland data sets recently assembled and checked by Dr. Tagir Gilmanov. These data sets cover a wide range of climate and "continentally" (increasing maximum summer temperatures, decreasing precipitation) from the North-West to the Southeast of the Commonwealth of Independent States (former U.S.S.R.).

The Khomutov study site (47.17 N 38.0 E) is situated close to the city of Mariupol (former name Zhdanov) in southeast Ukraine, near the Black Sea. This kind of steppe was once widespread around the Black Sea Lowlands, and is typically mowed annually.

Four years of aboveground biomass, dead matter and litter data are available for each growing season as well as a winter season data for December each year. There is also a single value of peak biomass from July 1948 (Gilmanov, 1996b).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1967 – 1970 for grid number 38056. The aboveground biomass production of LPJmL is compared with the measured living aboveground biomass (Figure 117). The calculated aboveground biomass by LPJmL underestimates the measured values.

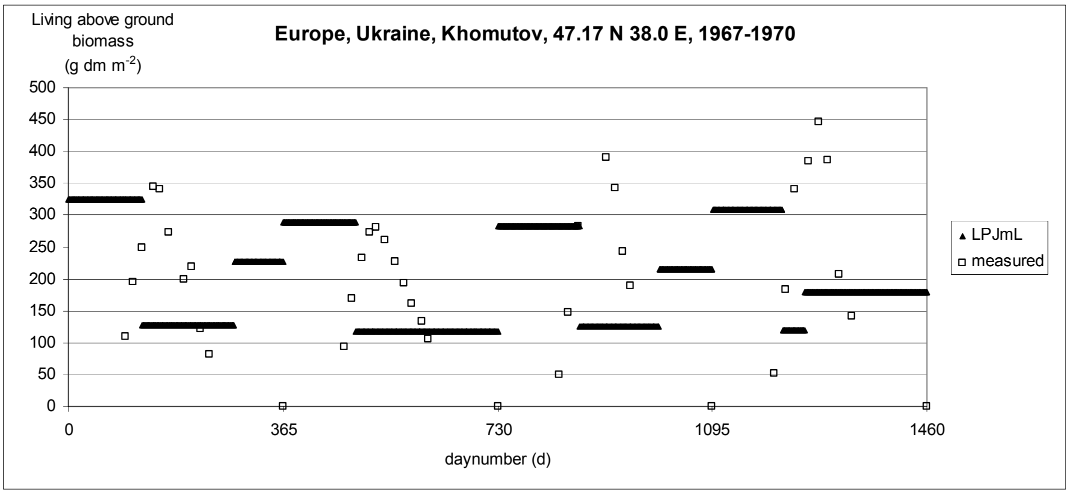


Figure 117 Measured and calculated living aboveground biomass in Khomutov, Ukraine from 1967 – 1970 (g dm m^{-2}).

The increment of biomass by LPJmL seems to fit the measured aboveground biomass, since the increment of biomass by LPJmL is the total biomass (above and belowground biomass together) the development shown by LPJmL is delayed compared to the measured values (Figure 118).

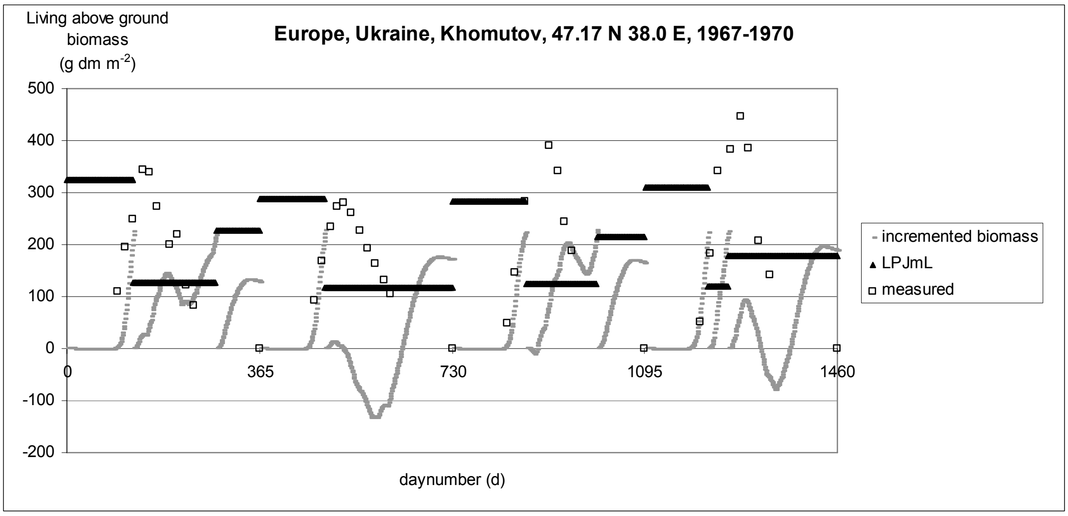


Figure 118 Measured and calculated living aboveground biomass and biomass increment by LPJmL for Ukraine, Khumutov, 1967–1970 (g dm m^{-2}).

5.1.8.7 United Kingdom, Beacon Hill

Description

Productivity of chalk grassland was studied from 1972 to 1973 at Beacon Hill, West Sussex, U.K. (Figure 119). Measurements of aboveground live biomass and total dead matter were made approximately bi-monthly. Aboveground net primary production was estimated by several methods, including peak live biomass, peak total live and dead, and accounting for turnover determined from marked leaves.

The 20 x 20 m study site (50.92 N 0.85 W) was located on the western slope of Beacon Hill, about 30 km northeast of Portsmouth. It is representative of the grasslands established over several hundred years by sheep grazing on the chalk hills of southern England. The climate is very mild and temperate, with relatively warm winters and rainfall distributed throughout the year. Grazing by sheep and rabbits had declined in the 20 years prior to the study, and had been very light since 1970.

Figure 119 General view of the Beacon Hill grassland site, UK. (Photograph taken 1973 by Dr. P. Williamson, University of East Anglia, UK).

Figure 120 Clipped sampling quadrate at the Beacon Hill grassland site, UK. (Photograph taken 1973 by Dr. P. Williamson, University of East Anglia, UK).

Detailed data on nine graminaceous species categories (92% of total matter) and a range of forbs is available from March 1972 to April 1973. ANPP was estimated at 355 g m^{-2} yr^{-1} (peak live biomass), 773 g m^{-2} yr^{-1} (max live + dead), 310 g m^{-2} yr^{-1} (sum of positive increments in biomass) or 691 g m^{-2} yr^{-1} (accounting for leaf turnover). In example of the clipping is given in Figure 120.

Monthly climate data for 1969–1993 are available from the weather station at the former King's College London field centre at Rogate, 6 km distant (51.01 N 0.85 W); daily climate data are also available for this site on special request from the ORNL DAAC User Services Office (Williamson & Pitman, 1998).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1972 – 1973 for grid number 26154. The calculated living aboveground biomass production by LPJmL is compared with the measured living above biomass (Figure 121). The calculated aboveground biomass by LPJmL matches the measured values, there is not much room for improvement (besides the $alpha_a$ = 0.5 factor).

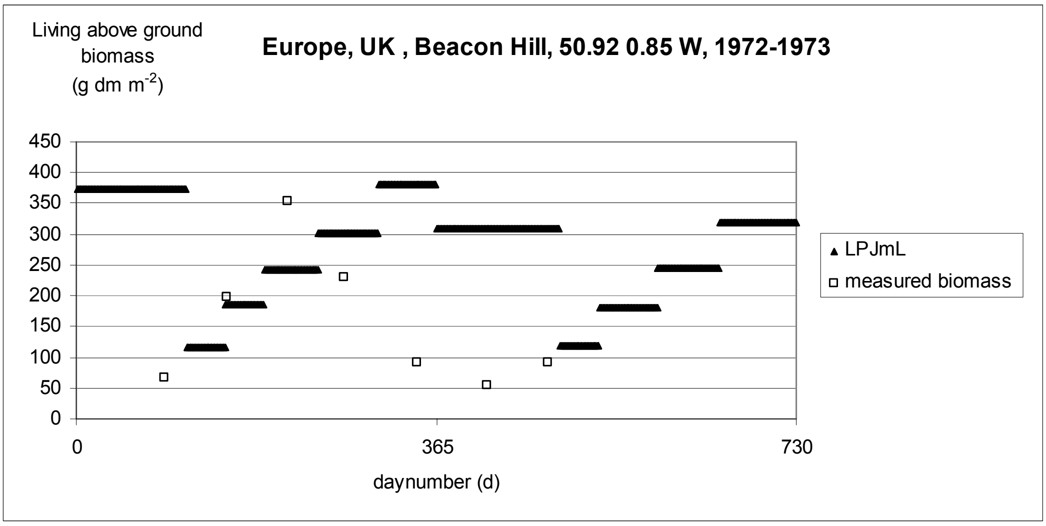


Figure 121 Measured and calculated living aboveground biomass of Beacon Hill, United Kingdom from 1972 – 1973 (g dm m^{-2}).

5.1.8.8 Sweden, Tullgarnsnaset

Description

Productivity of a seashore meadow was studied from 1968 to 1969 at Tullgarnsnäset, near Stockholm, Sweden. Measurements of aboveground live biomass and total dead matter were made approximately monthly. Belowground biomass was measured, but data were not reported. Aboveground net primary production was estimated by several methods, including peak total live and dead, and accounting for mortality determined by several different methods.

The study site (approximately 59.2 N 17.5 E) was located just above sea level on the Näset peninsula, about 45 km southwest of Stockholm. It is typically grazed, with a growing season of about 210 days. Detailed data for at least five species categories are available from April 1968 to April 1969. Using a variety of methods of calculation, ANPP estimates ranged from 324 g m^{-2} yr^{-1} (max live + dead) to 430 g m^{-2} yr^{-1} (accounting for disappearance of dead matter). In the absence of a long-term climate data set for this site, an alternative climate data set is provided for Stockholm, Sweden (59.4 N 18.0 E) (Wallentinus, 1997).

Comparison of calculations of LPJmL and measured data

LPJmL is run for 1968 – 1969 for grid number 30521. The calculated living aboveground biomass production by LPJmL is compared with the measured living above biomass (Figure 122). The calculated aboveground biomass by LPJmL overestimates the measured values.

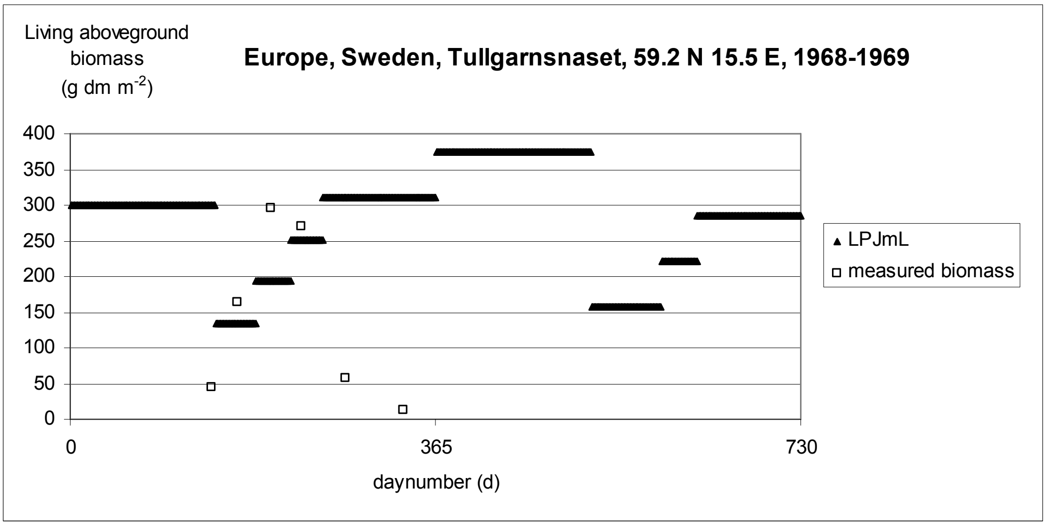


Figure 122 Measured and calculated living aboveground biomass of Tullgarnsnäset, Sweden from 1968 – 1969 (g dm m^{-2}).

5.2 Global grass production

With LPJmL, the global rainfed grass production is calculated. The simulation is run with grass as the only crop hence, keep in mind that areas with high grass production are mainly used for crops (east of North America and Europe) or occupied by tropical forest (areas around the equator).

In Figure 123 the total annual rainfed biomass production in kg dm ha^{-1} yr^{-1} calculated by LPJmL is given. The total production is the aboveground and belowground biomass, with dead matter included.

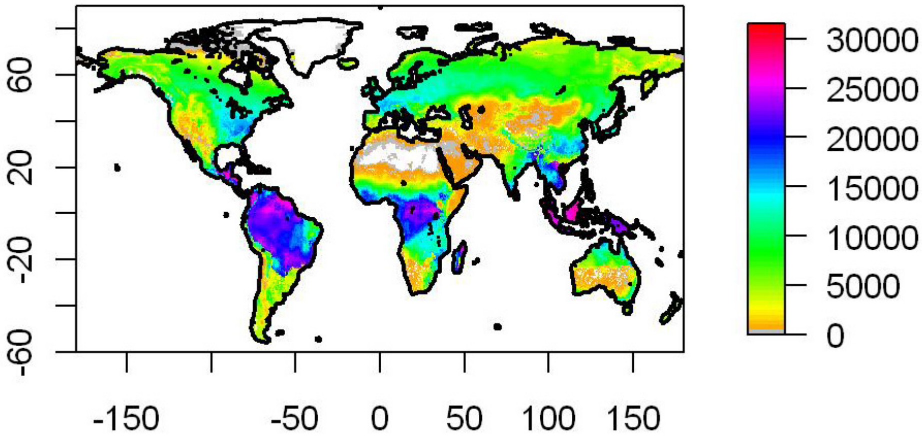


Figure 123 Average total global annual biomass for rainfed grass (kg dm ha^{-1} yr^{-1}) for 2000–2001.

In Figure 124 the calculated **available** global grass production under rainfed conditions for the year 2000 is given (parameter harvest in LPJmL, (g dm m^{-2} yr^{-1}). This is the estimated amount of grass available for animal feed. There are large areas where no grass seems to be available like the west of the USA, around the Sahara desert into China and Mongolia, South Africa and central Australia. These are low productive areas but according to Figure 123 there is grass production. Hence, the available grass in these low productive areas is underestimated by LPJmL, caused by the determination of the harvest moment by LPJmL (see section 4.3.5). For some regions, the allocation of dry matter to the roots is overestimated by LPJmL, which also may cause underestimation of the harvest (Africa subsection 5.1.1.2, Australia paragraph 5.1.4, Mexico subsection 5.1.6.1).

In Figure 125 the estimated global **demand** for grass per grid for the year 2000 (g dm m^{-2} yr^{-1}) is given. High grass demands (total grass consumption of Figure 137, IMAGE) exists in the east of North America, Western Europe and around the equator with exception of Africa.
In Figure 126 the **ratio** of global grass demand and production in 2000 is given (grazing intensity of Figure 137).

The most important areas in Figure 126 are those with ratios above one where the grass consumption exceeds the grass production with the risk of overgrazing and environmental damage like India, Asia and Argentina. It would be expected that areas as Mongolia would have a ratio over one as well as this area is known for its sensitivity to overgrazing.

Ratios below one indicate higher grass production than consumption. In areas with ratio 1–0.5 the demand is close to the production limit; the amount of animals that can be fed by the system is at its maximum (Europe including Russia, parts around central Australia and around the prairies of North America, South China).

Areas with ratios between 0.5 and 0.1 suggest grassland overproduction and a possibility to increase grassland use and feed more animals. However, as mentioned before, areas with high grassland production are often used as arable land rather than grassland. On the other hand, there are low productive areas with ratio between 0.1–0.5 like Namibia and Botswana (around the Kalahari Desert) and the boundaries around the other dry areas (Sahara, Gobi desert). It seems obvious that there is little room for increase of animal production in these areas.

With an increase of meat demand for human consumption and only slight changes in the global extent of grassland (Bouwman *et al.*, 2006) the pressure on the existing grasslands will increase with an expected increase of areas with consumption/demand ratios larger than 1.

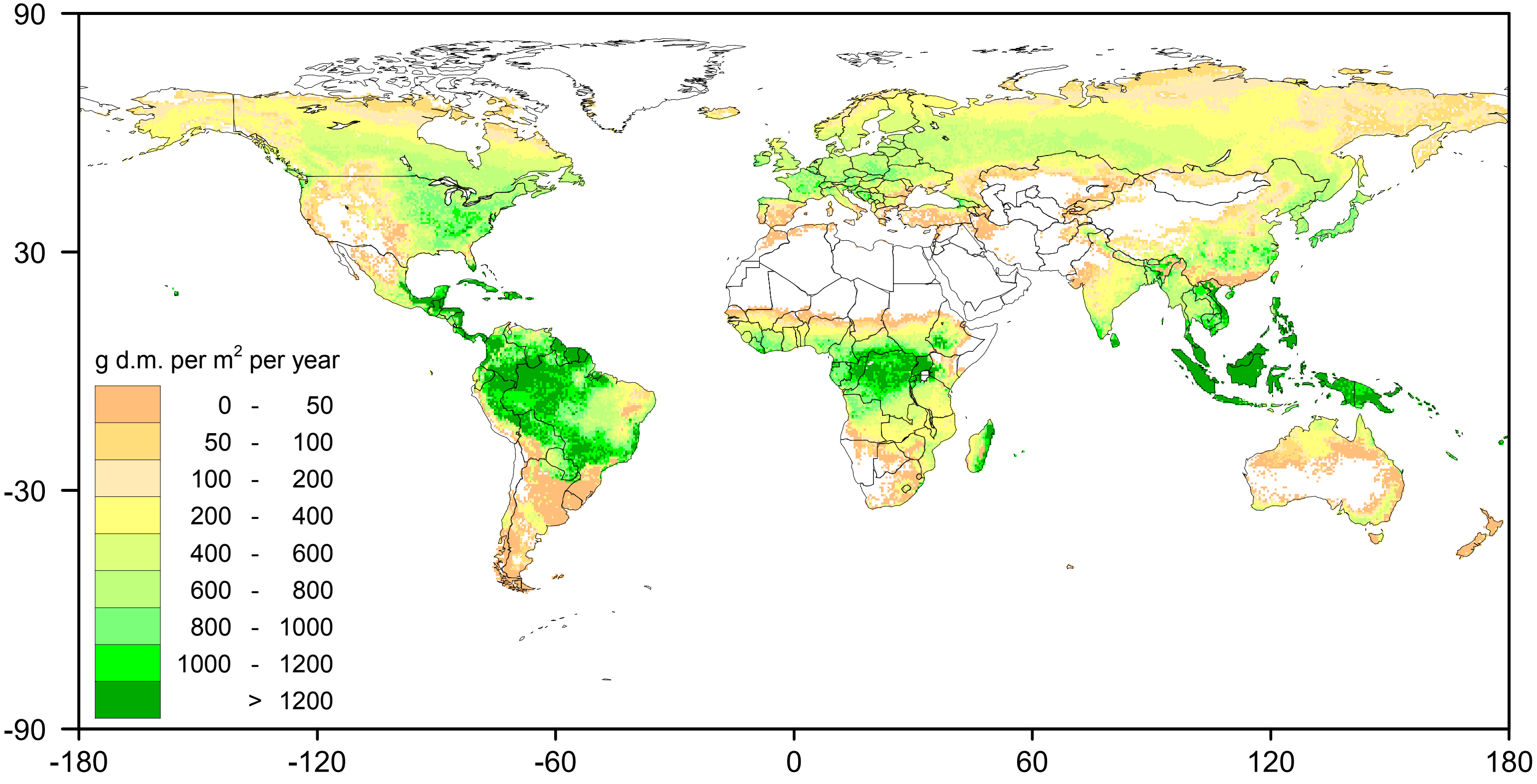


Figure 124 Worldwide available grassland calculated with LPJmL under rainfed conditions (2000) (g dm m^{-2} yr^{-1}) (Pers. Comm. L. Bouwman, PBL, 2010).

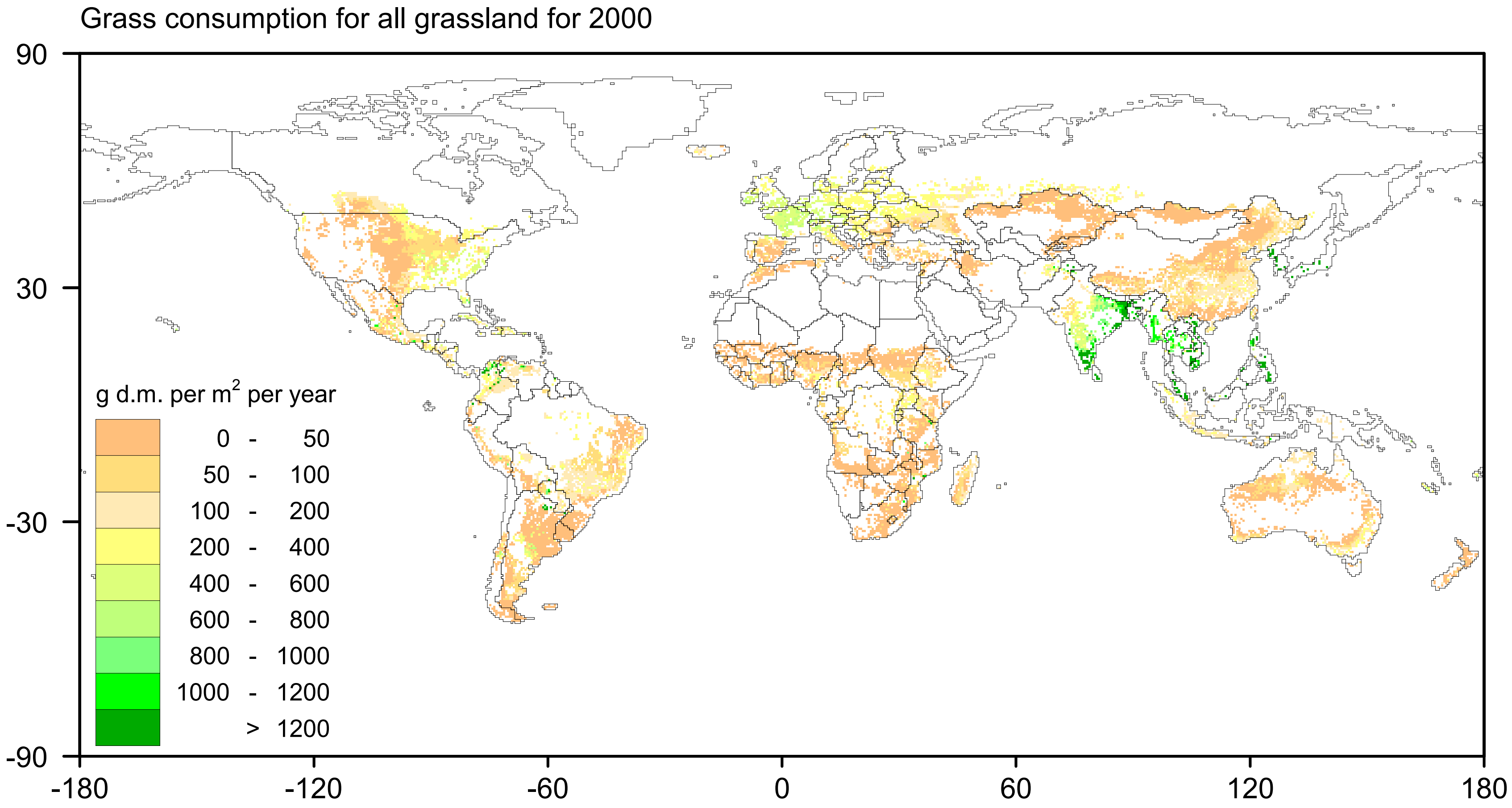


Figure 125 Global grass consumption as estimated with IMAGE 2.4 model for 2000 (Pers. Comm. L. Bouwman, PBL, 2010).

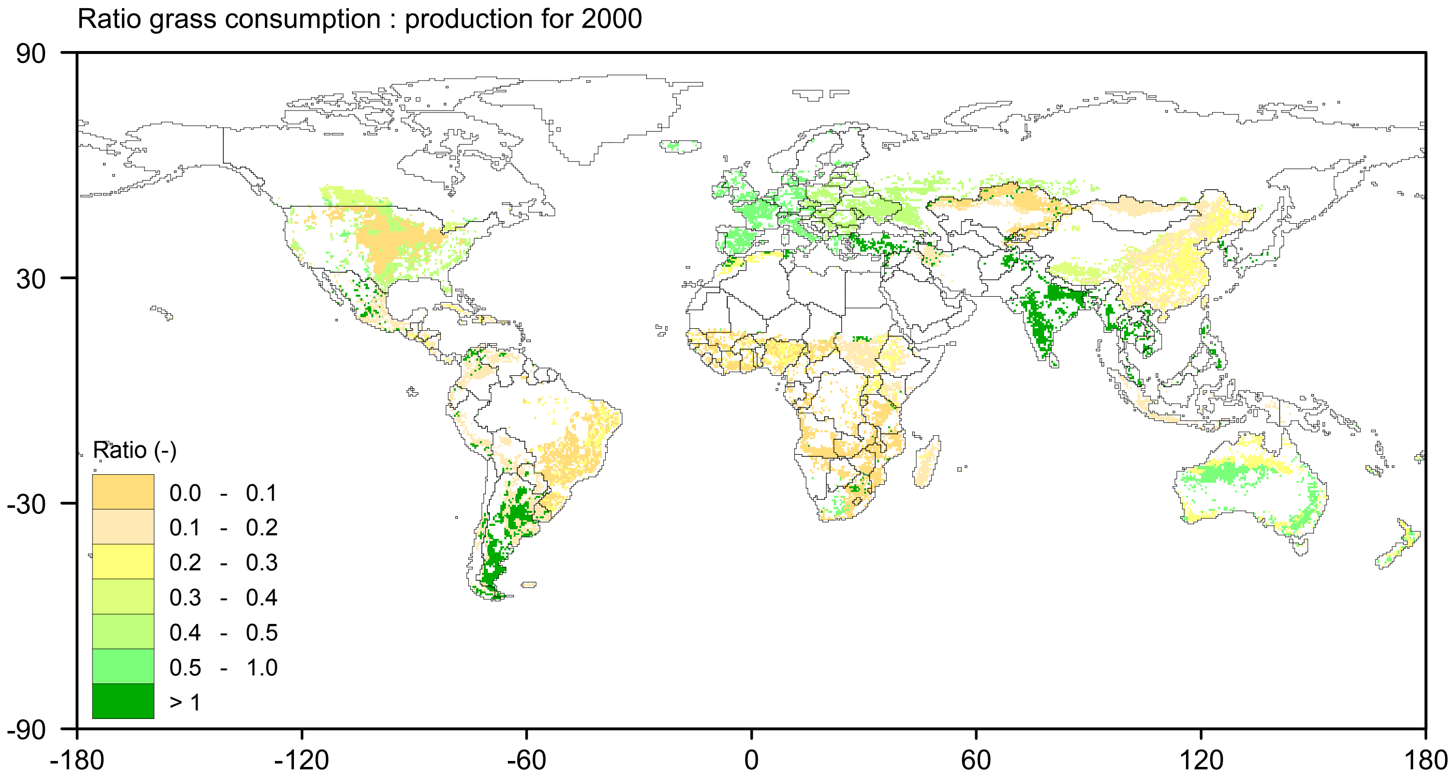


Figure 126 Ratio of global grass consumption and available grass in 2000 (Pers. Comm. L. Bouwman, PBL, 2010).

5.2.1 Conclusions about the comparison of water limited grass production of LPJmL with measured data

1) - LPJmL calculates the net rate of change of carbon per day and accumulates the carbon during inter harvest periods (parameter bm_inc). LPJmL allocates the accumulated net carbon amount to leaf, root and litter only on a harvest moment.

At a harvest moment, the amount of incremented carbon produced between harvests is first divided between roots and leaves. Than, half of the amount of carbon in the leaves is harvested and the remainder stays in the leaves. Because the amount of carbon in the harvested leaves, is half the amount of aboveground carbon in living leaves, the aboveground carbon from LPJmL may be calculated as the amount of carbon in the leaves times two. (If a quarter of the amount of carbon of the leaves would have been harvested the aboveground carbon would have been calculated by the amount of carbon in the leaves times four.) Even after this adjustment, it is difficult to compare the total aboveground carbon of biomass in measurements (g C m^{-2} or g dm m^{-2}).

In LPJmL, the senescence of the grass is not calculated during the growing season but, apparently, an amount of carbon in the leaves is sent to litter when the root/shoot ratio is too low (may be the first harvest) (see conclusion 3 on this item) and at the end of the year. This causes a continuing increase of the calculated amount of carbon in the leaves during the growing season whereas the measured amount of carbon in living leaves reduces towards the end of the year (Figure 127 which is the same as Figure 57 from 5.1.1).

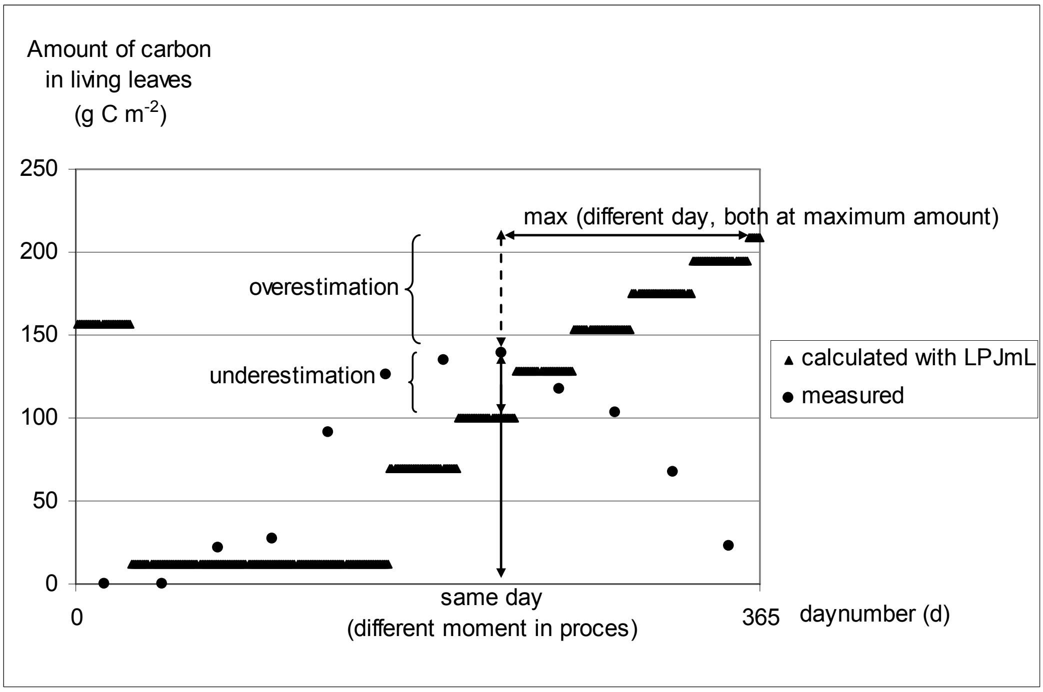


Figure 127 Measured and calculated amount of carbon in living leaves (g Cm^{-2})

The comparison between measured and calculated carbon production may take place on the same day (but with different amounts of carbon produced, Figure 127,'same day') or the maximum production of the calculated and measured data can be compared (on different days) (Figure 127, max).

This prohibits a correct comparison of measured and calculated carbon:

- on the same day, because the calculated value has not reached its maximum on the day the measured value has and this suggests an incorrect underestimation by LPJmL.
- at maximum production, because than the timing is wrong.

Recommendation: total amount of accumulated carbon allocated to the leaves, roots and above- and belowground litter should be provided in the output by LPJmL. This is a matter of output regulation.
Recommendation: allocations of carbon to roots and leaves should take place on a daily basis to solve this problem.

(The first options would be a matter of output regulation; the second option is more fundamental and demands to reconsider a part of the model structure.)

2) - In the model, the leaf area index (LAI) is calculated by multiplying the amount of carbon in the leaf (constant between harvests) by the SLA (which is a constant) and the phenology (which increases from 0 to 1 after a harvest). During the period after the harvest, the LAI increases until the value of the phenology is 1, than the LAI stays on that level until the next harvest because the amount of carbon in the leaves does not change between harvests.

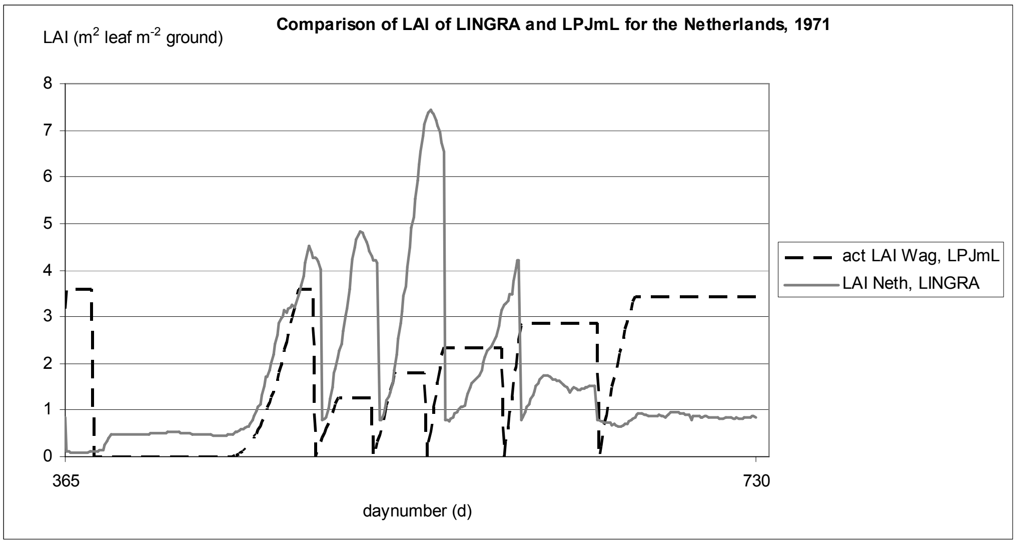


Figure 128 Comparison of LAI between LPJmL and LINGRA.

For example, the LAI of LPJmL starts with 3.8 than decreases to 1.3 and increases towards 3.5 at the end of the year (Figure 128). For LINGRA, the maximum values of the LAI between the harvests follow a curved line. The first maximum LAI, calculated by LINGRA, is 4.3, the second maximum LAI is 4.8, next 7.4 and than a decrease to 4.1 and 1.8 (Figure 128).

The constant value of the LAI, calculated by LPJmL, between harvests is no problem, but there is quite a difference in dynamics of the constant value of LAI between the harvests during the year between LINGRA (and nature) and LPJmL. High levels of LAI at the end of the years suggest a high interception of light at the end of the year, which does not happen in reality because of a decrease in amount of (carbon in the) leaves.

Recommendation: when the previous problem (1) is solved according to the second recommendation, the LAI will follow a more natural course as well.

3) - As long as only the amount of aboveground biomass is asked for, LPJmL calculates the amount of grass quite well for half of the experimental sites (Figure 129 which is the same as Figure 59 in 5.1.1). However, if more detailed information is needed, like the decrease of grass production at the end of the year, this is not simulated according to the measured data. In LPJmL, the senescence of living tissue is not based on physiological processes such as ageing of leaves or an exponential decrease with a relative mortality rate. The senescence of leaves is mimicked by sending carbon of the leaves to leaf litter at two possible occasions. One occasion is when the root/shoot ratio is too low and the amount of carbon in the leaves needs to be reduced (this happens sometimes at the first harvest). The other occasion is at the end of the year (day 365) when half of the leaf biomass is allocated to leaf litter and half to harvest.

Recommendation: If the allocation of biomass to roots and leaves is changed to a daily event, it is possible to take the senescence into account in the process.

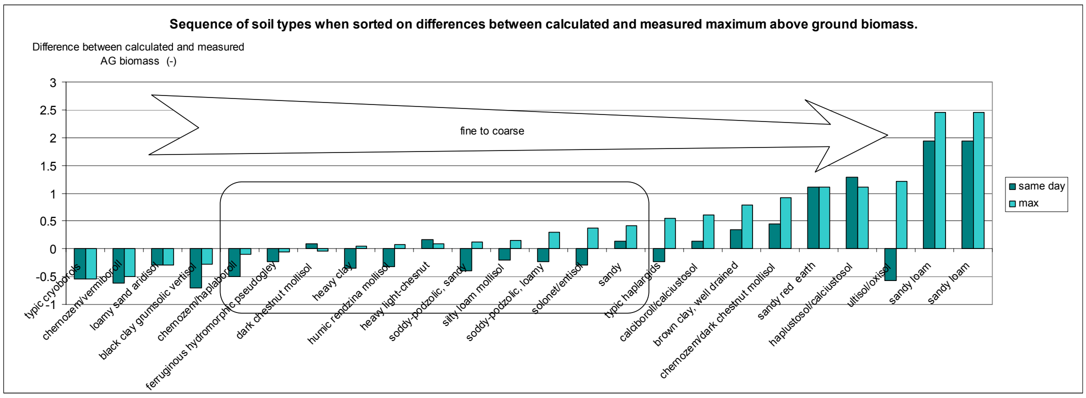


Figure 129 Difference between calculated and measured maximum aboveground biomass on the same day (same day) and measured maximum aboveground biomass in comparison with the maximum aboveground biomass LPJmL calculates for that year (max) per soil type sorted for 'max'.

4) - In 14 of the 23 investigated experiments, the graph of the aboveground biomass has the same shape as the graph of the measured aboveground biomass at the beginning of the growing season. This means that the amount of calculated aboveground biomass increases with the same rate as the measured aboveground biomass does when the growing season starts. But in 9 cases the calculated biomass seems to lag behind in time compared to the measured data, sometimes due to a delay in harvest moment, sometimes due to delay in growth.

When only the total harvest at the end of the year is of interest (and not the biomass increment from day to day) this is no problem.However, with grazing scenarios the grazing capacity will be underestimated when compared with the harvest (available fodder).

Recommendation: to be able to investigate grazing scenarios with LPJmL, the reasons for the seemingly retarded aboveground biomass development (as compared to data) and the daily available amount of biomass should be known.

5) - When harvest conditions are not met, the current threshold amounts to 100 g C m^{-2} together with a value one of the phenology, there is no harvest. This leads to an underestimation of the potential carrying capacity of the land for low productive areas like

Mongolia (see comparison between calculated total living biomass and calculated available biomass).

Recommendation: living aboveground biomass calculations should be provided in the output by LPJmL together with harvest values.
Recommendation: investigation on the effect of lowering the threshold of 100 g C m^{-2} on living aboveground production and harvest.

6) - When the global harvest of LPJmL is compared with the global demand for grass of IMAGE, some places like Mongolia seem to have an excess in grass. When the grass consumption (IMAGE) is divided by the grass production (calculated by LPJmL) this ratio is 0.1 for Mongolia (overgrazing has a ratio value > 1). This is strange, because there tend to be overgrazing in this area. Either LPJmL overestimates the grass production or the grass demand (amount of grass eating animals) from IMAGE is too low. The density of grazing animals in IMAGE is calculated as the total number of animals, divided by the land area of the whole of the country. This approach causes a low animal density and assumes that bare soil is also grazed.

Recommendation: One way to solve this problem is to allocate grazing animals to grass producing grids only. This needs to be fixed between the two models LPJmL and IMAGE. To get an idea of the potential production and carrying capacity it is valuable to have the aboveground biomass and the harvest in the output.

7) - In LPJmL, the absorbed photosynthetically active radiation (APAR) is a parameter from the photosynthesis function, used to calculate the carbon production. APAR is calculated from the photosynthetically active radiation (PAR, J $m^{-2}d^{-1}$) multiplied by the fraction of incoming PAR intercepted by green vegetation (FPAR, (–) and $alpha_a$ (–). This $alpha_a$ is an empirical parameter that accounts for reductions in PAR utilization efficiencies in natural ecosystems and is assigned a value of 0.5 based on quantum efficiencies from field and laboratory measurements. This reduction factor is quite substantial (in comparison to 1) and when the total calculated biomass matches the actual measured biomass as is the case in Thailand, there is no room for management factors like fertilization and pests and diseases. For managed grassland, $alpha_a$ could be made a function of these management factors.

Recommendation: the effect of $alpha_a$ on the grass production calculated by LPJmL needs further investigation; what is the exact meaning of $alpha_a$ and is it necessary. In particular, it should be clarified whether management factors are taken into account elsewhere in the model, or that $alpha_a$ could be used for that purpose.

8) - For Dutch practice, LPJmL does not reach the very high and validated production levels of LINGRA.

Recommendation: maybe this problem is solved when the $alpha_a$ parameter is set to one. Otherwise, the assumptions on LAI and the water supply and demand should be checked.

The following conclusions are about the choice for C_3 or C_4 grasses in LPJmL. The choice for C_3 or C_4 grasses by the LPJmL model is based on a temperature threshold. When the average minimum temperature over 20 years is below 15.5 ˚C, LPJmL chooses C_3 for a grid and above this threshold LPJmL calculates the carbon production for a C_4 grass.

9) - When LPJmL is run for the SINGLECROP and GRASSLAND option, for a location where C_3 or C_4 grass species grow, the calculated accumulated biomass is given correctly in the output. However, when both plant species occur in the same grid the C_4 output overwrites the C_3 output.

Recommendation: when both C_3 and C_4 grasses are present in a grid both carbon productions should be available in the output. This is a matter of output regulation.

10) - The model LPJmL wrongly chooses C_3 instead of C_4 on at least two locations; India and Spain. These are locations with great differences between cold and warm periods (seasons, day/night). This leads to an average minimum temperature over 20 years below the 15.5°C threshold and LPJmL chooses C_3 instead of C_4, which is the local dominant grass species.

C_4 plants are rare at altitudes and latitudes where growing season temperatures are less than an average of approximately 16°C and minimum midsummer temperatures average less than 8°C to 12°C (Long, 1983). Thus, not the average minimum over 20 years should be above 15.5°C, but the average temperature should be above 16°C and the minimum midsummer temperature should be above 8°C to 12°C. Moreover, for locations with monsoon-climates, the distribution of the precipitation is important too (Sage, 1999).

Another example of the role of water is an experiment in Mongolia where a shift to C_3 occurs instead of C_4 when the circumstances are drier. However, this may be a local reaction and too detailed for a global simulation model.

Recommendation: the deciding parameter for C_3 and C_4 grasses (average minimum temperature over 20 years) and the necessity to implement dependence of C_3 or C_4 choice on precipitation distribution needs further investigation.

11) - In the model, the phenology is the same for C_3 and C_4 grasses, although the phenology of these grass species is different see Figure 130, same as Figure 133 from section 6.3 (Sage, 1999).

Recommendation: investigation of phenology for C_3 and C_4 grasses.

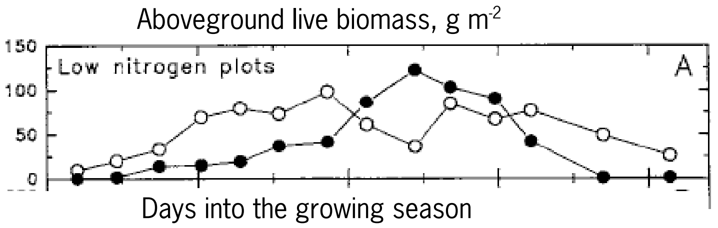


Figure 130 Seasonal patterns of aboveground live biomass for C_3 (open circles) and C_4 (closed circles) vegetation in an east-central Minnesota sand prairie. Low nitrogen plots were unfertilized. Day 0 of the growing season is April 15. (D. Wedin, 1985, unpublished data. See Tilman, 1988, for details of the study site and methods) (Sage et al., 1999).

12) - In LPJmL, the allocation of accumulated biomass to roots and leaves is determined by a parameter called `lmtorm`. This parameter is calculated as the parameter lmro_ratio (0.75 (-) times the available water in the previous period (wscall_mean/365), hence it does not depend on grass species. However, there is a big difference between C_3 and C_4 grasses in allocation ratio. In Australia an endemic C_3 grass has a shoot/root ratio of one ((122 g m^{-2})/ (110 g m^{-2})) and C_4 (buffel grass) a shoot/root ratio of 0.4 (154 g m^{-2})/ (400 g m^{-2})).

Recommendation: both the 0.75 and the effect of the water balance on the allocation parameter and LPJmL calculated grass production needs further investigation.

13) - High overestimations of aboveground living biomass (Figure 131 same figure as Figure 58 from 5.1.1) may be caused by an overestimation of water availability
on course sandy soils.

Recommendation: on course soils, the water balance and water holding capacity needs further investigation with respect to calculated grass production by LPJmL.

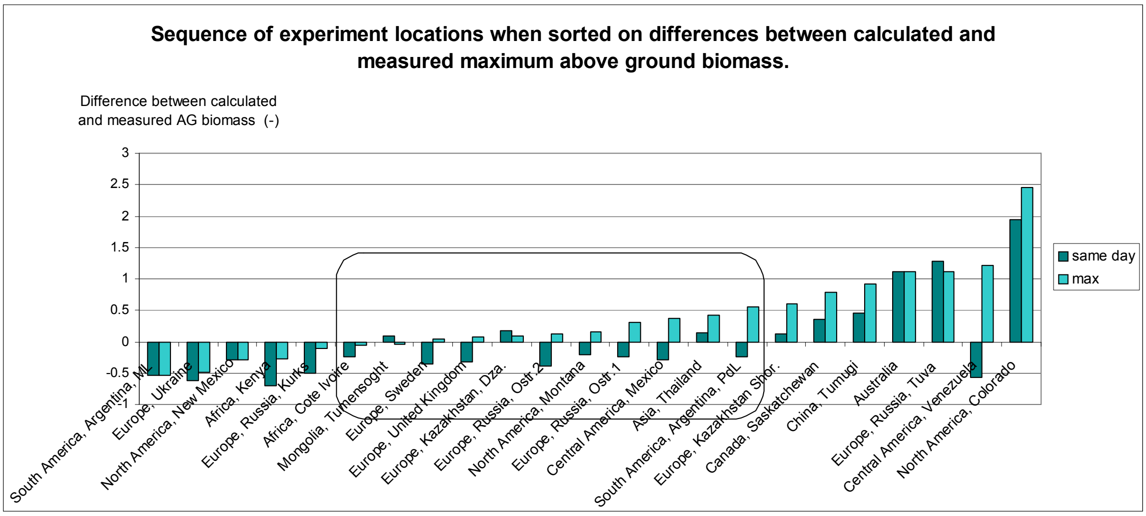


Figure 131 Difference between calculated and measured maximum aboveground biomass on the same day (same day) and measured maximum aboveground biomass in comparison with the maximum aboveground biomass as calculated by LPJmL for that year (max) per region, data sorted for 'max'.

14) - In LPJmL there is one fixed value for SLA = 0.04 m^2 leaf g^{-1} C leaf. This may be too rigid. SLA of perennial grasses has values between 0.03 and 0.06 m^2 g^{-1} C leaf, but annuals have higher levels between 0.06 – 0.08 m^2 g^{-1} C leaf.

Recommendation: the effect of different SLA values on calculated biomass production by LPJmL should be investigated (sensitivity analysis).

15) - During a global run, the check of the carbon balance may cause an error message.

Recommendation: investigate the cause of the problem; a suggestion is to perform a carbon balance check at the end of each year.

5.2.2 Conclusions about the code

1) There are too little literature references in the code (almost none) to indicate the origin of the calculation rules or values of parameters.

2) Variables change in value when used in calculations like

a) In fscanpft_grass.c line 76, 77 the values of `cn_ratio.root` and `cn_ratio.leaf` changes

```
cn_ratio.root = respcoeff*k/cn_ratio.root
cn_ratio.leaf = respcoeff*k/cn_ratio.leaf
```

b) In fscanpftpar.c line 126 the ramp changes value:

`pft->ramp=1/pft->ramp`, where the ramp has a value 100 this changes to 0.01.

c) In fscanpftpar.c line 123 the SLA changes value from 0.5 from pft.par to a fixed value 0.0411 (m^2 leaf g^{-1} C leaf):

```
pft->sla=2e-4*exp(6.15-0.46*log(pft->longivity*12))
```

d) In fscanpft_grass.c line 73, 74 the value of `turnover.leaf` and `turnover.root` is changed.

```
grass->turnover.leaf=1.0/grass->turnover.leaf
grass->turnover.root=1.0/grass->turnover.root
```

e) In next table fscan means: read parameters from file, or another parameter. `pft->respcoeff` goes to `pft->name,respcoeff.` etc but `longivity` becomes `sla=2e-4*exp(6.15-0.46*log(pft->longivity*12))` without any warning in the code.

This is allowed in C but confusing for the user.

/* 8. pft */
C3_PERENNIAL_GRASS
"C3 perennial grass"
GRASS

file pft.par		file fscanpftpar.c	
value	description		comment
1.2	respcoeff	fscanpftreal(isout,file,&pft->respcoeff,"fscanpftpar",pft->name,"respcoeff");	ok
0.5	sla 10	fscanpftreal(isout,file,&pft->longivity,"fscanpftpar",pft->name,"longivity"); sla=2e–4*exp(6.15–0.46*log(pft->longivity*12));	very confusing
100	ramp 19	fscanpftreal(isout,file,&pft->ramp,"fscanpftpar",pft->name,"ramp");	ok

It is no exeption that values are given in the code, whereas they should be defined and given in the parameter list.

First example: The parameter frac from file Litter_update_grass.c gets the value 0.5 in file harvest_stand.c

File Litter_update_grass.c
`Harvest litter_update_grass(litter, pft, frac, isharvest )`

File Harvest_stand.c
`harvest = litter_update(litter,pft,0.5,TRUE)`

Second example: In allocation_grass.c, fpc_grass.c and turnover_grass.c the parameter nind is used. This parameter gets its value (pft->nind=1) in init_grass.c. The parameter list or pft.par would be a better place.

3) There is little attention for the units of variables and names of parameters are sometimes confusing.

6 Management

6.1 Introduction

The former part of the report paid attention to the water limited grass production caused by the natural environment as calculated by the model LPJmL. In this chapter, the influence of humans on grass production is taken into account.

Grasslands are of vital importance for raising livestock for human consumption and for milk and other dairy products. Grassland vegetation remains dominant in a particular area usually due to grazing, cutting, or natural or manmade fires, all discouraging colonization by and survival of tree and shrub seedlings. Some of the world's largest expanses of grassland are found in African savanna, and these are maintained by wild herbivores as well as by nomadic pastoralists and their cattle, sheep or goats. Hunting peoples around the world often set regular fires to maintain and extend grasslands, and prevent fire-intolerant trees and shrubs from taking hold. The tallgrass prairies in the American Midwest may have been extended eastward into Illinois, Indiana, and Ohio by human agency. Much grassland in northwest Europe developed after the Neolithic Period, when people gradually cleared the forest to create areas for raising their livestock
(http://en.wikipedia.org/wiki/Grassland#Human_impact_and_economic_importance).

Human utilization of grasslands can be scaled from extensive to intensive. There is a whole range of measures humans can apply to change grassland production to meet their needs. They can choose another grass species rather than a native one, a C_3 of C_4 type of grass, amount of animals per area, animal species and breeds, irrigation, use of fertilizers or legumes, fire and a choice between mowing or grazing are important ones and some will be discussed in the light of LPJmL. For this study C_3/C_4 grasses, amount of animals and animal species, legumes, fire and use of fertilizer are chosen (Figure 132). The gray parts of this figure are applied in LPJmL the white parts not (yet).

The items of Figure 132 will be discussed in the next sections.

6.2 IMAGE

This project was started to get an idea of the validity of LPJmL and to propose improvements for the calculation of grass production. The intention is to incorporate LPJmL in the Integrated modeling of global environmental change model (IMAGE2.4). IMAGE is build to be able to investigate the global impact of human activities on natural and managed ecosystems by running all kind of climatic scenarios.

It could be a suggestion to let IMAGE influence the choice of the grass type, i.e. C_3 or C_4, instead of accepting the automatic choice of LPJmL. If, for instance, the IMAGE user wants to compare the grass production with a C_4 grass in Australia LPJmL has to be informed that is should run with C_4 for Australia.

Furthermore, if the user wants to calculate the effect of a higher harvest frequency this is not yet possible, because the model decides internally what the harvest frequency will be. The same applies for fire. It should be possible to choose in IMAGE whether fire is used and how often.

Figure 132 Possible management measures to improve calculations of water limited grassland production with LPJmL.

6.3 C_3/C_4

The physiological aspects of C_3 and C_4 plants are described in 3.1.4. Here the management aspects of C_3 and C_4 plants are given. There are regions dominated with either C_3 or C_4 grass species. However, there are also regions where C_3 and C_4 grass species coexist (Parton *et al.*, 1995). C_3 grasses may start in the cool spring and the C_4 grasses may take over during the hot summer. This is an important feature in the light of fodder production because this extents the fodder production season. In Minnesota (United States) sand prairies, C_3 plants normally dominate aboveground live biomass in the spring and fall, whereas C_4 grasses dominate production in June through August, when average daily high temperatures exceed 25°C (Figure 133).

Although the environment dictates the suitability for C_3 or C_4 grass species, farmers experiment with other grass species. The data of the Australia site Charleville where the native C_3 grass is replaced with an imported C_4 grass species is an example of this behavior. Figure 81 in 5.1.4 shows an increase from measured dry matter from 75 (C_3) to 100 g m^{-2} (C_4). The total aboveground dry matter yield was 182 and 319 g m^{-2} yr^{-1} for the native and introduced grass sites respectively (Christie, 1999).

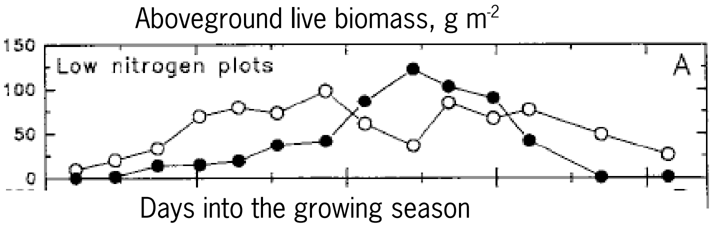


Figure 133 Seasonal patterns of aboveground live biomass for C_3 (open circles) and C_4 (closed circles) vegetation in an east-central Minnesota sand prairie. Low nitrogen plots were unfertilized. Day 0 of the growing season is April 15. (D. Wedin, 1985, unpublished data. See Tilman, 1988, for details of the study site and methods) (Sage et al., 1999).

The biomass yield of buffel grass (C_4) is higher than that of native grass ($C_{3)}$. Because of the higher nitrogen use efficiency of the buffel grass, this grass produces more biomass per unit nitrogen, hence less nitrogen is necessary to produce the same amount of aboveground biomass. The nitrogen content in buffel grass is lower than in native grass (Figure 134 and Table 13).

The aboveground biomass times the nitrogen content gives the nitrogen yield. When the temperature is high (23-35°C), the nitrogen yield of C_4 grasses is higher than the C_3 grass, but at low temperature (13-24°C), the nitrogen yield is the same for both grass species (Table 13, Figure 135).

It seems that an animal needs less forage of the C_4 grass when the temperature is high and the same amount of forage when the temperature is low. This is only valid when the digestibility of dry matter, crude fiber and crude protein (to name a few) are compatible for C_4 and C_3 grasses, but this needs further investigation (Christie, 1999) (Figure 134).

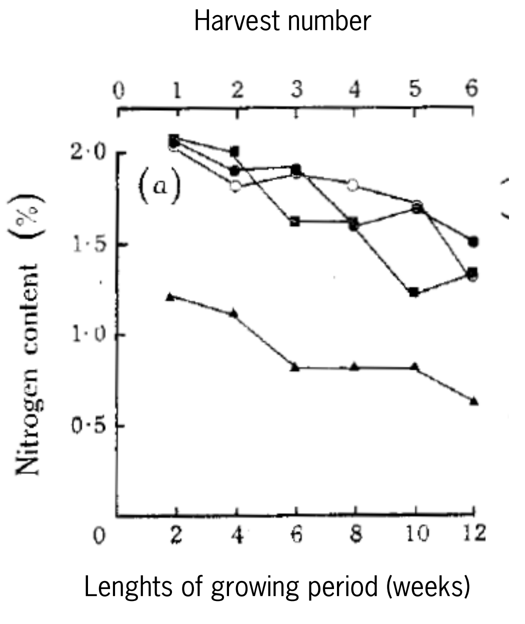


Figure 134 Changes in nitrogen content (oven dry basis) of buffel (black squares), mulga Mitchell (black circles), mulga oats (open circles) and kangaroo (black triangles) grasses over a continuous summer growing period (Christie, 1979).

Table 13 Grass dry matter yields and N content at various levels of N fertilization (Brown, 1978).

Reference	**N applied**	**Dry matter yield**		**N concentration in forage**		**N yield**	
	kg ha^{-1}	kg m^{-2}		% dry matter			
		C_3	C_4	C_3	C_4	C_3	C_4
Hallock *et al.*,1965	112	38	83	2.52	2.13	0.96	1.77
	224	58	114	2.77	2.26	1.61	2.58
	448	72	161	3.25	2.75	2.34	4.43
	896	69	175	3.50	3.00	2.42	5.25
	g/pot						
Colman and Lazenby, 1970; 23 to 35˚C	0	12	33	2.50	0.91	0.30	0.30
	67	20	48	2.20	0.94	0.44	0.45
	134	20	60	2.61	1.17	0.52	0.70
	269	31	65	2.90	1.78	0.90	1.16
Colman and Lazenby, 1970; 13 to 24˚C	0	11	22	1.82	0.91	0.20	0.20
	67	20	35	2.63	1.18	0.50	0.41
	134	27	41	2.17	1.61	0.59	0.66
	269	35	48	2.78	2.00	0.97	0.96

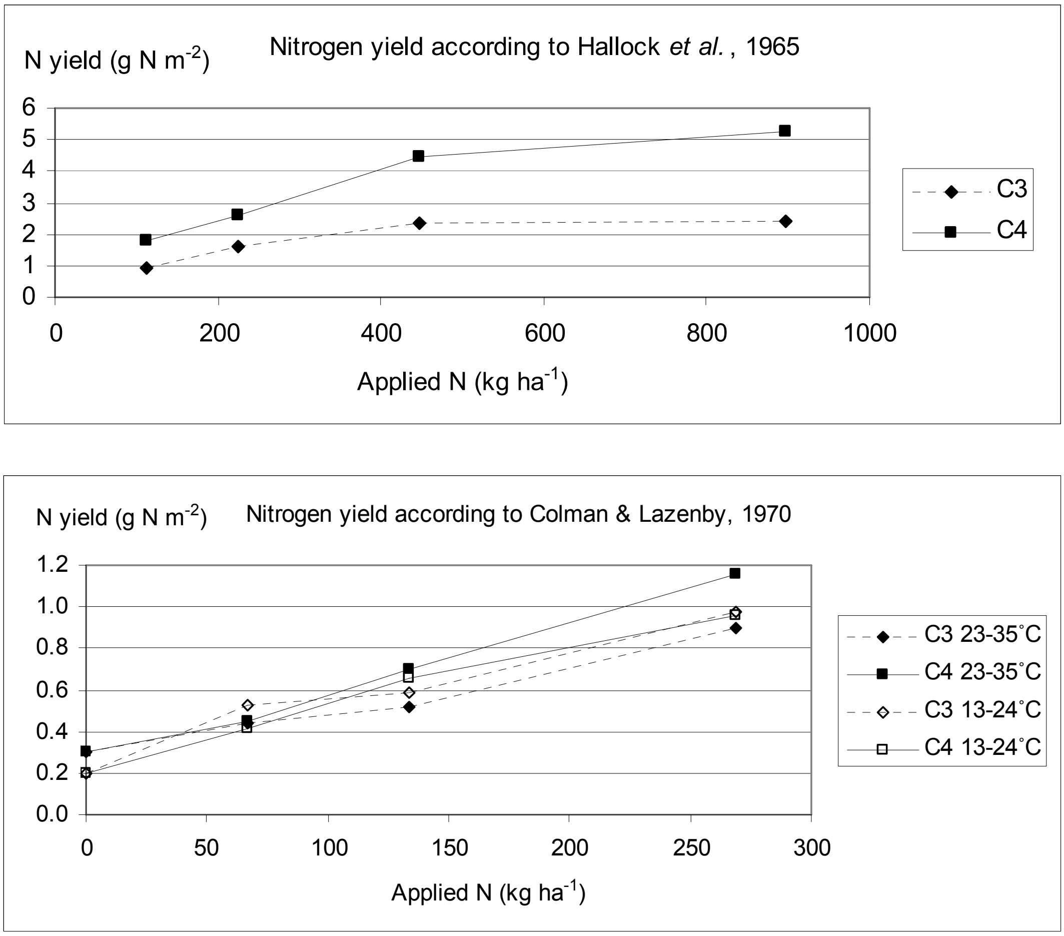


Figure 135 Nitrogen yield (g N m^{-2}) depending on nitrogen application (kg ha^{-1}), (Brown, 1978).

6.4 Land use intensity

The definition of an extensive used grassland system is grasslands with low management input. This means that the input of tillage or sowing with preferred grass species or legumes and use of fertilizers, herbicides and pesticides is low or zero. Herdsman travels around with herds or herd of animals roam freely and are round up at specific times of the year. Examples are the savannas of Africa and Australia and the pampas of Argentina.

The definition of an intensive used grassland system is grasslands with high management input. The management makes intensive use of the resources with high input of tillage, swat improvement by sowing desired grass and/or legume species and input of manure or fertilizers and even irrigation. It may be expected that these systems are high yielding. These systems exist in Western Europe, North America and Canada and parts of India. None of these aspects is considered in the LPJmL grassland part. They could be provided by IMAGE input.

In IMAGE three systems of land, use exists mixed, pastoral and marginal. This is based on the percentage of grassland in a grid cell (Figure 136). The pastoral system rely mainly on grazing by ruminants, whereas mixed/landless systems have integrated crop and livestock production in which animal's diets consist of a mix of several feedstuffs. In the mixed/landless systems, the by-products of one activity (crop by-products, crop residues and manure) serve as inputs for another (Bouwman *et al.*, 2006). Pastoral systems are accounted to a grid cell when > 75% of the grid exists of grassland. Grassland grid cells with lower percentage grassland are considered mixed of landless livestock production systems. The database of IMAGE contains information about the amount of animals per species and region/area and their diet. The need for fresh grass is one aspect and this can be compared with the harvest data calculated by LPJmL. It may be possible that different management systems are introduced in LPJmL i.e. high and low yielding grasslands depending on the information given by IMAGE input.

6.5 Legumes

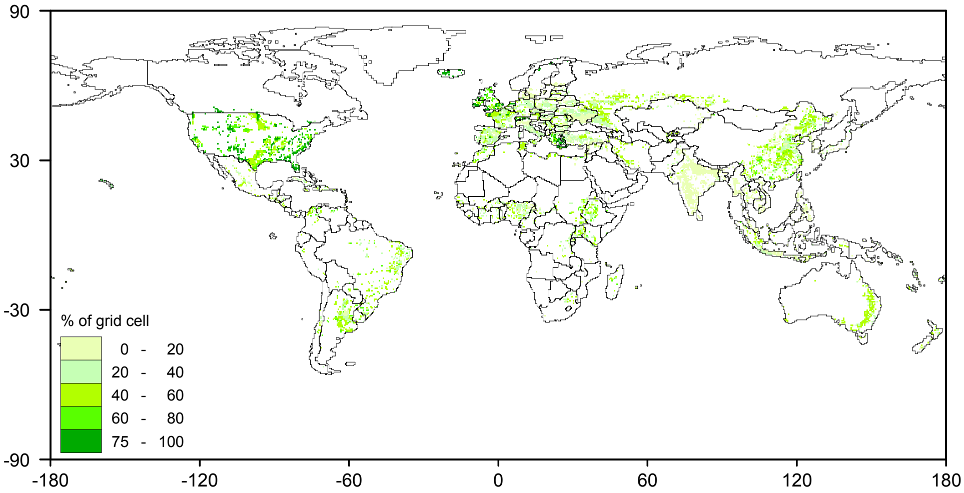
Legumes provide a natural source of nitrogen for grasses. In most (natural) grasslands legumes exists. In extensive used grasslands, legumes are used to improve grassland production and quality like in New Zealand. In systems that are more intensive, they tend to disappear with raising nitrogen levels in the soil. The interest in legumes returns with legislations and restrictions on fertilizer usage. As long as the calculated biomass in LPJmL does not depend chemical characteristics this cannot be taken into account. Legumes can provide from 30 – 215 kg N ha^{-1} when phosphorus needs are met (Schils, 2002).

Soil fertility and fertilizers

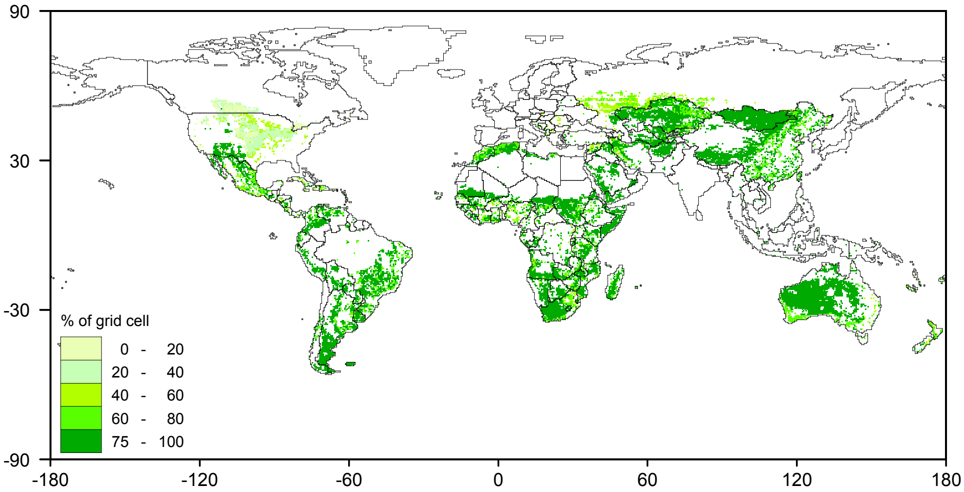
In extensive used grassland systems, the grass production depends on natural soil fertility, native legumes and depositions by wandering herds. No fertilizers are brought in from outside the system.

In intensive grassland systems, fertilizers for nitrogen, phosphate and potassium may be used to increase grass and animal production and grass quality. Intensive grassland production systems tend to produce a lot of animal manure. The farmers use this to reduce the need for fertilizers. An advantage of the use of manure instead of fertilizers is that animal manure contains organic matter, which supports soil characteristics like structure and moisture containing capacity. A disadvantage of manure is that the farmer has less control of the proportion of different chemicals (N, P and K) in applied manure and a risk of spreading pests and diseases. There is a connection between soil moisture and pH and availability of nutrients for the plant.

Industrial + mixed systems



Pastoral grassland



Marginal grassland

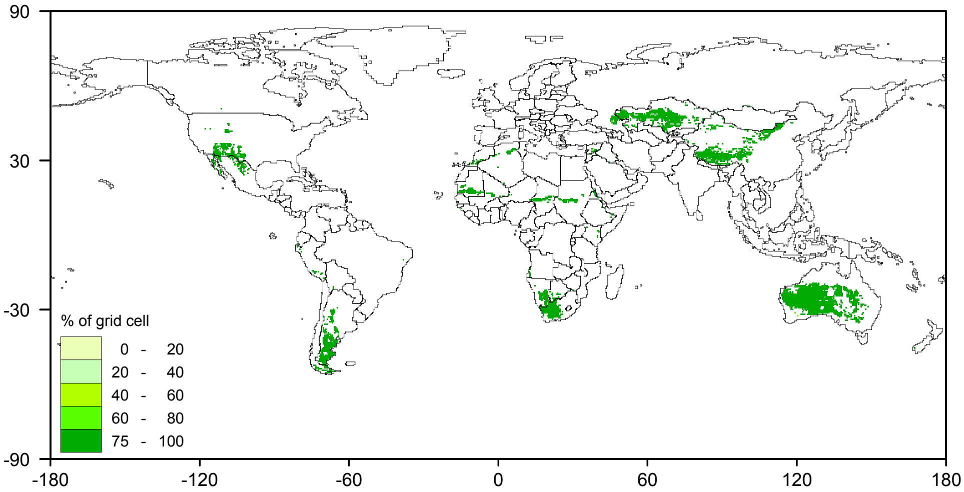


Figure 136 Distribution of mixed, pastoral and marginal grasslands (IMAGE, 2000) (Pers. comm. L. Bouwman, PBL, 2010).

Although manure and fertilizer application are among the first measures farmers use to improve grassland production it is not possible to take this into account as long as the calculated biomass in LPJmL only depends on physical environmental characteristics and not on chemical ones. Often the focus of fertilizers is on the quantity of the fodder but fertilizers change the quality of the fodder as well.

6.6 Fire

Fire plays an important role in grassland management and it serves several purposes:

- to clear the area from unwanted trees, shrubs and herbs;
- replacement of nutrients like phosphorus and potassium from the lower soil levels to soil levels within reach of grass roots;
- to renew the vegetation and promote young leaves (with higher digestibility and higher nutrient contents.

The frequency of fire use ranges from once a year to once in ten to twenty years.

PBL wants to run scenarios to investigate the effect of fire on the environment and grass and animal production. To accomplish this changes are needed in the interaction between IMAGE and LPJmL. Because the effect of fire on the nutrient availability is very important, nutrient based grass growth In LPJmL is needed to use the full potential of the model.

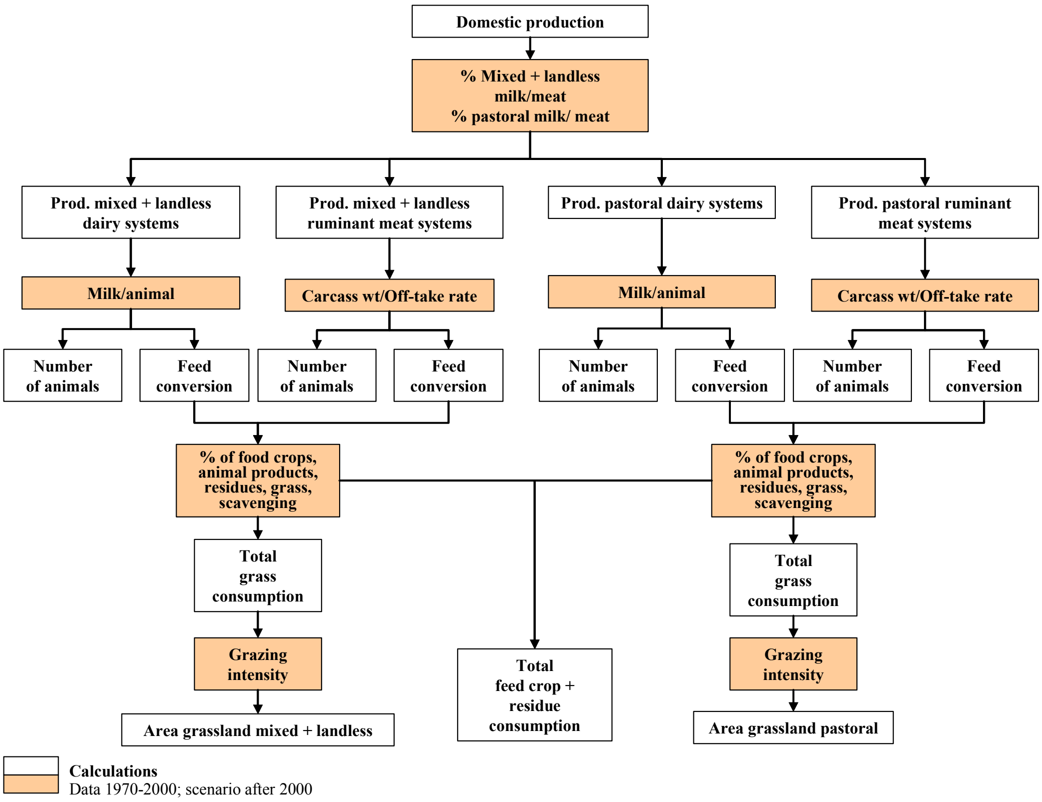


Figure 137 Livestock production and grazing intensity in IMAGE (Bouwman et al., 2006).

Animal density

It may be expected that the number of animals per ha for intensive grassland systems are higher than for extensive grassland systems. Higher input should lead to a higher output in yield and/or income.

LPJmL will be build in the IMAGE model. In IMAGE, three livestock production systems are distinguished, pastoral systems, mixed and marginal systems (Figure 136). In IMAGE, the distribution of livestock production over these three systems is known. For dairy cows, the number of animals and the milk production per animal is known.

Carcass weight and off-take rate for beef cattle, sheep and goats are presented. For these animals groups, feed conversion efficiency, composition of feed and finally total feed crops, residue consumption and area of grassland via grazing intensity are taken into account (Figure 137). In Figure 138, the amount of livestock units of pastoral systems is given and in Figure 139 the amount of livestock units in mixed systems.

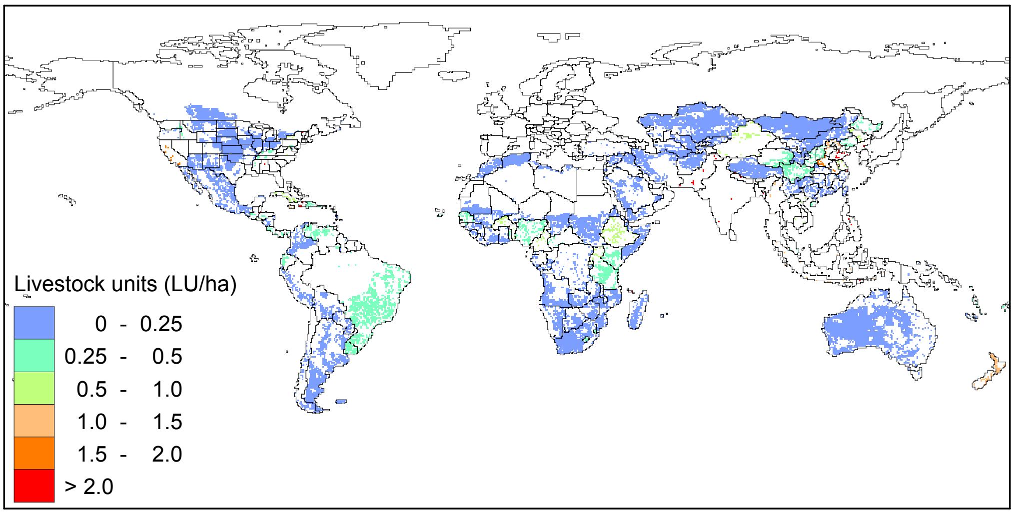


Figure 138 Livestock units of pastoral systems (IMAGE 2000) (Pers. comm. L. Bouwman, PBL, 2010).

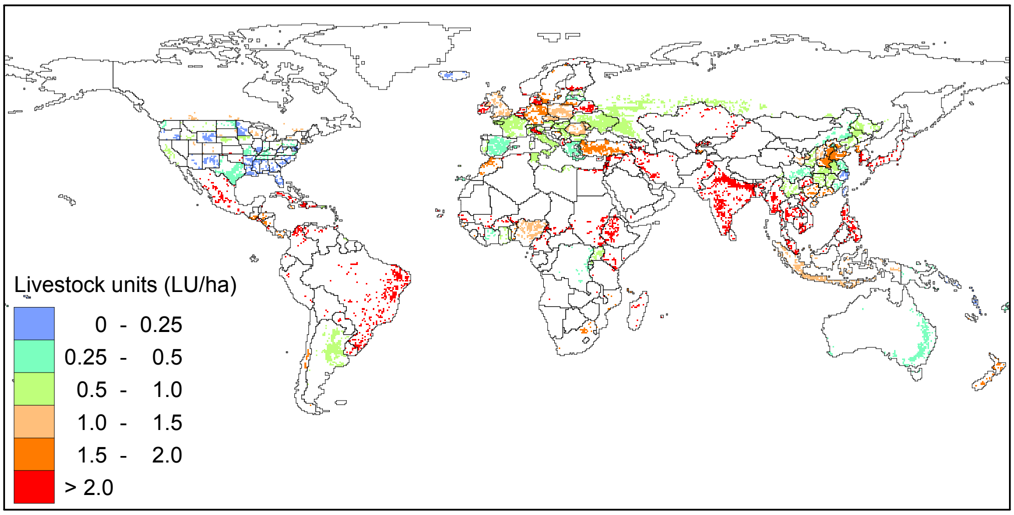


Figure 139 Global distributions of livestock units in mixed systems (IMAGE 2000) (Pers. comm. L. Bouwman, PBL, 2010).

In pastoral systems herdsman roam around with their herds. However, if the amount of herds increases because of socio-economic reasons overgrazing and degradation of the soil may become a threat like in Mongolia and Sahel. With al this information the total grass demand of a region is known and can be compared with the calculated grass production of LPJmL. This is done in 5.2 and Figure 126). However, grazing and mowing losses are not taken into account.

6.7 Mowing and grazing

6.7.1 Intensive grassland mowing and grazing

With intensive grassland systems, the animals are held in enclosures or meadows. There are even systems where the animals stay indoors all the time and fodder is mown or bought and brought in. Grazing animals causes more losses per ha than mowing, but is better for animal welfare.

Grazing with cows

The optimal amount of grass to graze cows on is 1700 kg dry matter/ha (76 g C m^{-2}) (about 15 cm high) with a maximum of 2200 kg dry matter ha^{-1} (100 g C m^{-2}) (17 cm high) under Dutch conditions. The stubble left by the animals is 5-6 cm (IKC, 1994). In UK grazing starts at a crop height of 20 cm to a stubble height of 5 cm (http://www.countrysideinfo.co.uk/ag_grasslnd/grazing.htm).

Mowing

First mowing harvest is best with a production of 2000 – 4500 kg dry matter ha^{-1} (90 – 202.5 g C m^{-2}) for the next harvests 3000–3500 kg ha^{-1} (135 – 157 g C m^{-2}) is the optimal dry matter level. To reduce frost damage it is advised not to mow after 1 October (IKC, 1994).

6.7.2 Mowing and grazing (losses)

LPJmL does not take grazing and mowing losses in to account. A proposal for these losses is produced on basis of land use intensity. It is assumed that a high ratio of grass consumption /grass production corresponds with a high utility level and hence high losses. This results in losses as suggested in (Table 14).

Table 14 Estimation of grazing losses depending on grass consumption (IMAGE)/grass production (LPJmL).

grass consumption (IMAGE)/grass production (LPJmL)	loss (%)
0.0–0.1	0
0.1–0.2	3
0.2–0.3	6
0.3–0.4	9
0.4–0.5	12
0.5–1.0	15
> 1	30

The result of these losses on the ratio of grass consumption/simulated grass production by LPJmL is given in Figure 142. This may be compared with Figure 126 the ratio of global grass consumption and available grass in 2000 without mowing losses. With mowing losses, it would be expected that the ratio grass consumption: production increases because the amount of production decreases. This would cause a shift from a lower ratio to a higher ratio (i.e. from ratio 0.2 – 0.4 to 0.4 – 0.6). This happens in regions like central Europe and Australia. However, there are regions with an opposite reaction like east China, Canada and southern parts of North America. This needs further investigation.

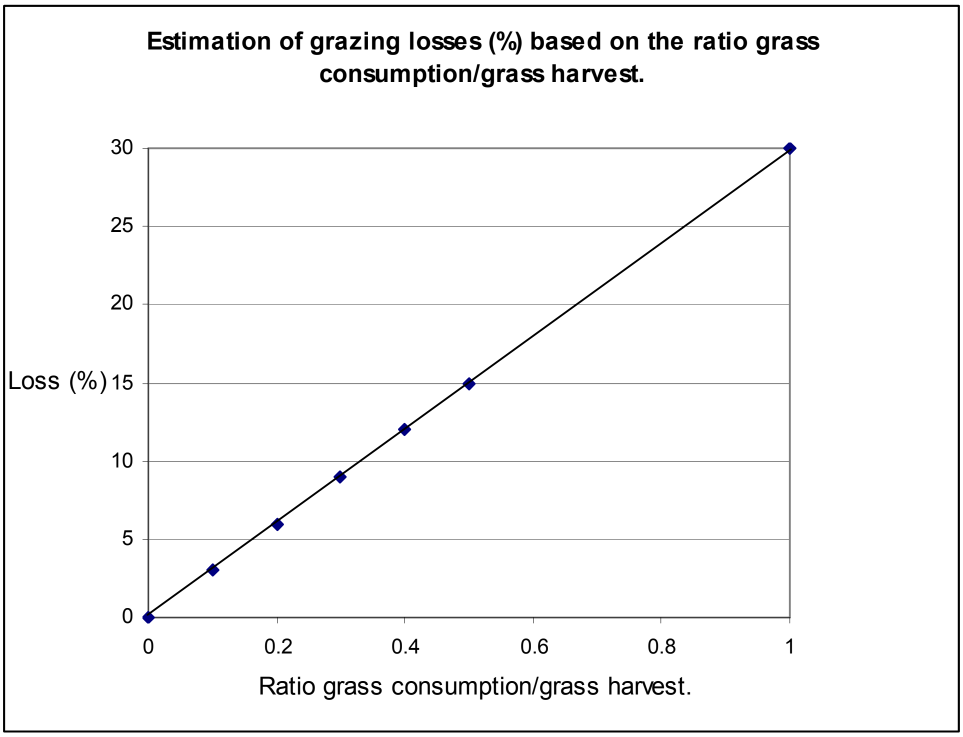


Figure 140 Estimation of grazing losses bases on the ratio grass consumption/grass harvest.

In Figure 141 the effect of mowing and grazing losses on the interaction between IMAGE and LPJmL is drawn.

6.8 Effect of harvest level on amount of harvested dry matter

To get an idea of the reaction of the amount of harvested dry matter under high or low harvest pressure LPJmL is run for three locations with a clear warm and cold season and some harvest levels.

The default threshold for harvest is 100 g C m^{-2} for incremented biomass. If this level is decreased an increase of grazing frequency is mimicked, hence a higher value indicates a lower grazing frequency. Both may lead to lower harvests for different reasons. With a high grazing frequency, the amount of remaining biomass is too small to sustain fast and thorough regrowth, the amount of harvested grass declines. With a low grazing frequency, grass at ground level is depleted from light and will wither; this declines harvest as well.

Table 15 and Figure 41 show the results for three different environments. In the Netherlands and China, a difference from the default threshold results in the predicted decline in amount of harvested carbon. In Canada (Saskatchewan) there is a slightly increase of harvest with a higher grazing frequency (or lower stubble left after grazing).

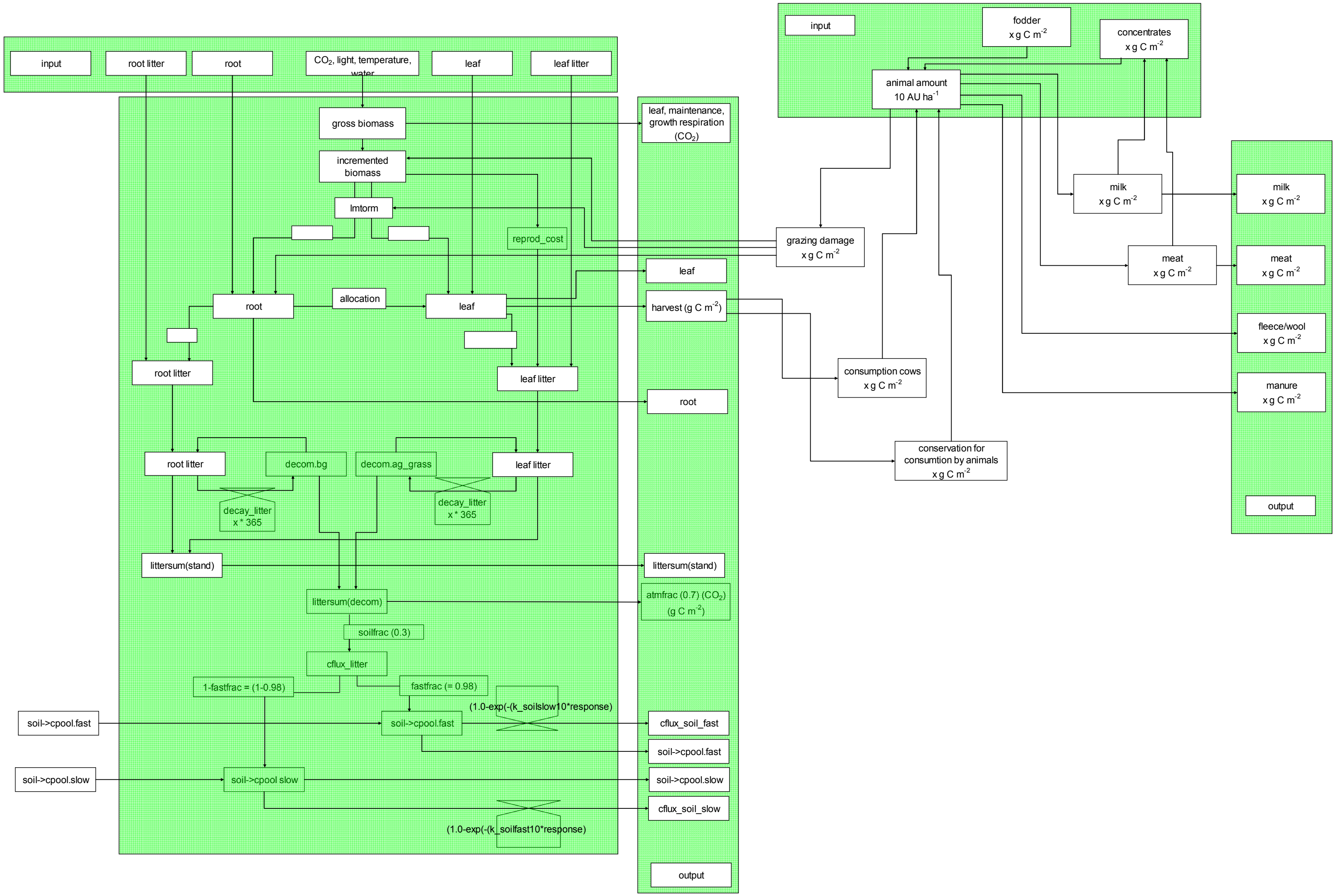


Figure 141 Flow chart of the effect of grazing and mowing losses in LPJmL on the carbon cycles.

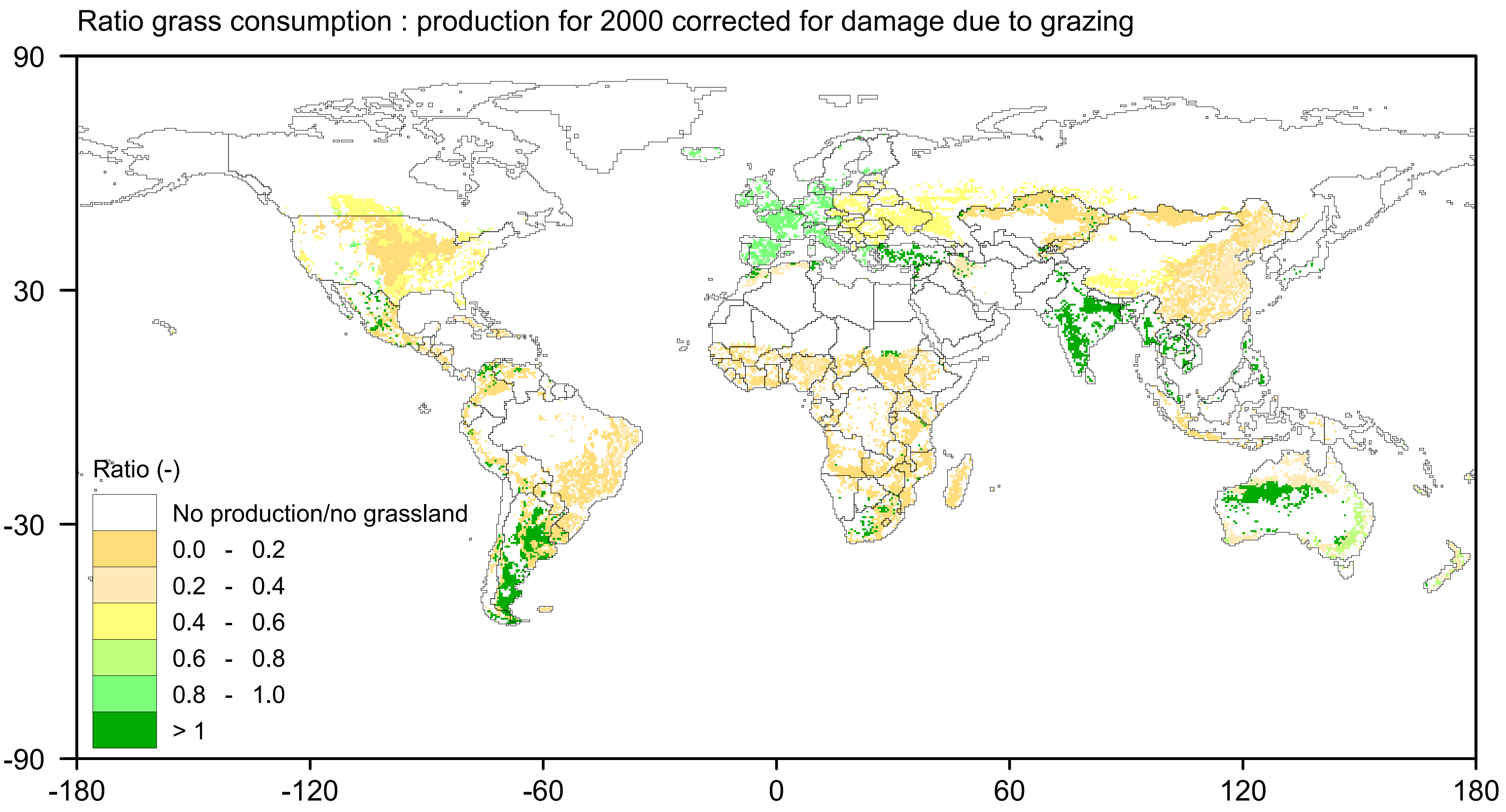


Figure 142 Ratio of grass consumption (IMAGE) and simulated grass production by LPJmL corrected for damage due to grazing (2000) (Pers. comm. L. Bouwman, PBL, 2010).

Table 15 Ten years average harvest at different harvest threshold for incremented biomass for three experimental regions.

Region	Grid nr	bm_inc level	Average harvest 10 years (g dm m^{-2})
the Netherlands 1967–1977	26837	150	249
		100	262
		50	250
		20	181
China 1980–1990	59486	150	134
		120	146
		100	159
		50	155
		30	146
		20	124
Canada 1967–1977	5543	150	97
		125	102
		100	97
		75	105
		50	110
		25	111
		20	109

6.9 Conclusions about management

1) - In IMAGE, the amount of grass needed for animal consumption is calculated. In LPJmL, the amount of harvested grass is calculated without taking into account the amount of grazing and mowing losses, which will reduce the harvest and increase the amount of litter.

Recommendation: Estimations of grazing losses depending on grass consumption (IMAGE)/grass production are presented in Figure 140.

2) - The model LPJmL decides internally where C_3 and C_4 grasses are grown. PBL would like to run scenario's with the option that when a farmer decides to grow a C_4 on a location where a C_3 grass usually grows or vice versa (less obvious).

Recommendation: It should than be possible that the IMAGE model controls this choice, rather than LPJmL.

3) - PBL would like to make scenario's to investigate the effect of fire (if the nutrients are added to LPJmL) hence this decision should be controlled by IMAGE (with the boundaries for litter and water content set in LPJmL as they are now).

Recommendation: It should than be possible that the IMAGE model controls this choice, rather than LPJmL

4) - IMAGE reports the amount of nutrients used per grid. These numbers could be explored by LPJmL if the model would be further developed to include nutrient dependent grass growth. In the developed regions like West Europe, the impact of adding nutrient depending growth may not be very large, but in the developing areas, this may be substantial. There are examples where low P and K inputs result in substantial yield improvements (Buresh and Giller, 1998 and Buresh *et al.*, 1997).

Recommendation: It would be an advantage if the presence of legumes could be accounted for in LPJmL, as legumes can e.g. contribute to up to 215 kg N ha^{-1} under Dutch conditions.

5) - The quantity of grass production is important, but the quality is the next challenge to accomplish. Quality has several aspects. Some important ones are mentioned here. The crude protein content is closely correlated to the amount of nitrogen. This plays a role with items like animal production (growth), legumes and fire. Another aspect is digestibility correlated to age of plant material and plant species (palatable grasses in comparison to thistles). There is no simulation of quality in LPJmL yet. It is to be expected that the effect of nutrients on yield and quality is higher in the tropics, with poor and phosphorous fixing soils with low organic matter, than in Western Europe.

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Annex 1: Flowchart of LPJmL

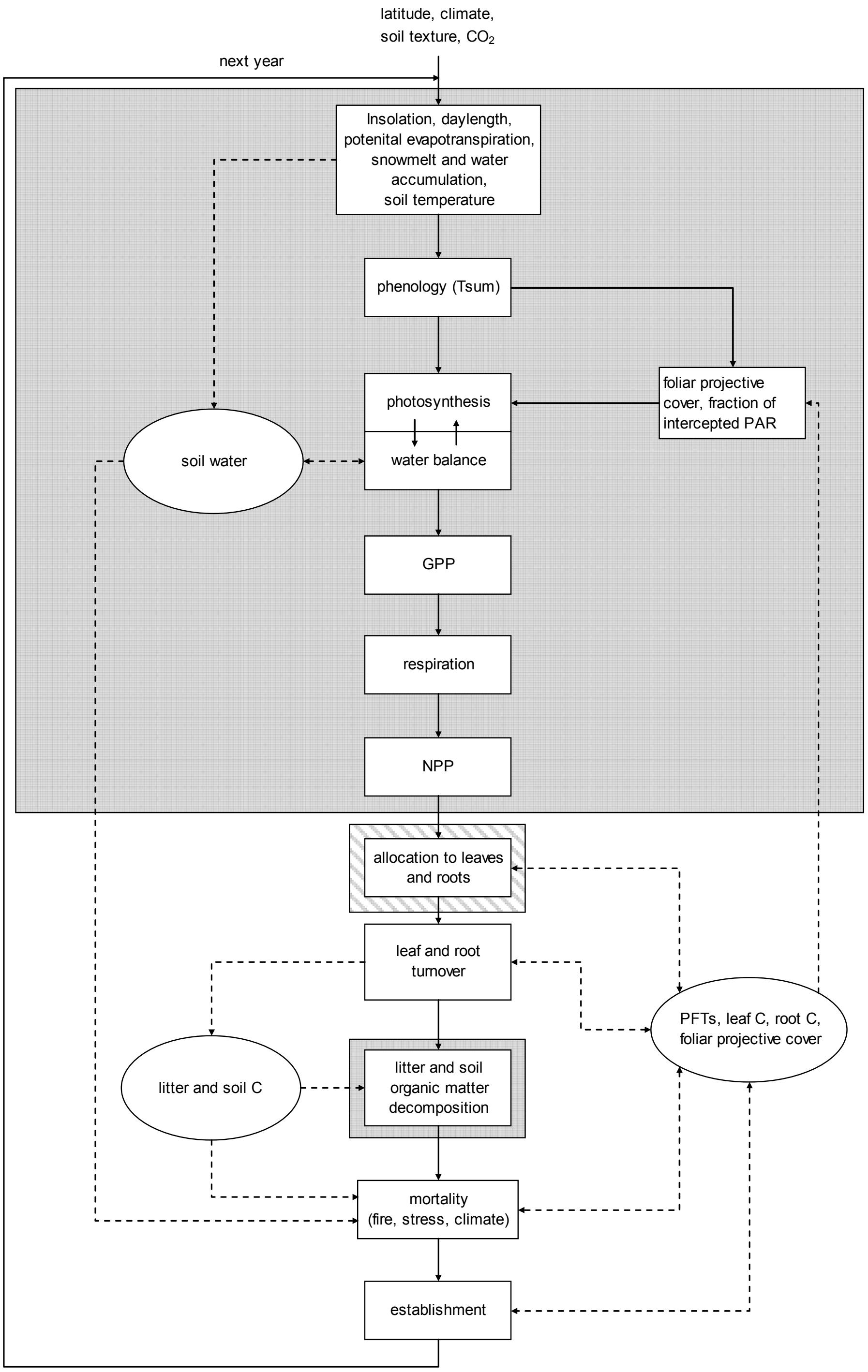

Figure 143 Global overview the processe of the grass part of LPJml (based on Sitch et al., 2003)

In Figure 143 the individual processes (boxes) and the order of processes (solid lines) are represented. These processes take place in all grid cells during one simulation year. The dashed lines represent exchange of information between vegetation and soil state variables and the individual processes with arrow representing the direction of information flow. Processes with a shaded background are called on a daily time step, the process with the striped background is called on a harvest moment, the remainder is called annually.

Annex 2: Test data per region

NPP Grassland: NPP Estimates from Biomass Dynamics for 31 Sites, 1948-1994

Summary

Field measurements of biomass and associated environmental data were compiled for multiple study sites in major grassland types worldwide. When sufficient biomass data were available, we compared NPP estimated by six different algorithms for 31 grassland sites to examine potential bias associated with the algorithms (Scurlock *et al.* 2002). This data set includes monthly grassland biomass data and NPP estimates produced by the different algorithms.

The data consisted of monthly measurements of biomass components including aboveground live material, standing dead, litter, belowground biomass, and belowground dead material. However, many of the sites did not collect all of the components. There are 1477 field measurements of some component of NPP, all sites having at least aboveground biomass measurements. Of the 31 sites, 20 also measured standing dead and litter or total live plus dead material. In addition, 17 sites measured total belowground biomass, and six of these sites provided separate measurements of live and dead root components. The study sites had from 1 to 29 years of biomass data with an average of 3 years per site. Five ecoregions were represented, including cold desert steppe, temperate dry steppe, humid savanna, humid temperate, and savanna.

The selection of study sites was based on the availability of complete and consistent information on NPP or at least partial NPP, together with the dynamics of live biomass and dead matter for at least the growing season (Scurlock *et al.* 2002). Site-description metadata, such as latitude, longitude, elevation, and information on vegetation type (biome), soil type, and land-use history were also desirable for inclusion for study sites in the compilation.

In addition, we included study sites that had at least one reference from the peer-reviewed literature. Quality assurance included mapping the points in geographical space to confirm that they coincided with landforms and checking data ranges for outlying values. For consistency, only measurements from long-term natural or ungrazed treatments were used in the analysis of Scurlock *et al.* (2002), although measurements are available for manipulated study sites from the ORNL DAAC's NPP Web site (see below). One of the 31 sites (i.e., Kurukshetra, India) appears to be an outlier because it has an ANPP that is 3 to 7 times that of the other grassland sites. The high NPP may be a consequence of some undocumented factor such as a previous history of fertilization at the study site. Because Kurukshetra meets all other criteria for inclusion, it is included here; however, users may choose to exclude it from their specific application.

We processed the original grassland biomass observations for each site to generate data sets that had common variable names, units of measure, and organization. For example, we assumed that the variables described in the original literature as outstanding dead, recent dead, dead were equivalent, representing plant matter which was produced and had died within the current year, and that the variables old dead and litterusually represent the accumulation of previous years' production. Some sites lacked desired information, such as the day of the month that measurements were recorded, or required decisions to assemble the data, such as combining aboveground and belowground measurements when the components were measured on different days. When possible in these cases, we examined the original literature or contacted the authors to confirm our data processing decisions.

Aboveground and belowground components were processed separately, and, if measurements for both components were available, ANPP and BNPP were summed to provide total NPP for the site. In the summary of annual NPP, sites with fewer than five biomass measurements for a year were dropped to ensure that the entire growing season was represented (assuming most sites measured biomass on an approximately monthly schedule). Climatological data for each study site (precipitation, mean monthly maximum temperature, mean monthly minimum temperature) were obtained from the original literature or the original authors, if available. Alternatively, we obtained the climate data from the nearest weather station (<10 km distant, and at similar elevation) if available from existing collections such as the National Climatic Data Center (Asheville, NC, U.S.A.) or the Carbon Dioxide Information and Analysis Center (CDIAC, Oak Ridge National Laboratory, Oak Ridge, TN, U.S.A.) see the individual sites' site descriptions for details and specific sources of climate data.

References for the source of site data and NPP estimates for specific years, biomass, climate, and other associated environmental variables for the 31 detailed study sites are available on the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) NPP Web site (http://www.daac.ornl.gov/NPP/npp_home.html). Many of the sites have data for multiple treatments as well as ancillary information such as site photographs and graphs of biomass dynamics and climate.

In addition to grasslands, the global database NPP from the ORNL DAAC includes forest sites based upon field observations (Scurlock and Olson 2002) to address the need for a high quality data to parameterize, calibrate, and validate terrestrial biosphere models (Olson *et al.* 2001). NPP estimates in the database draw primarily on the published estimates of NPP. While this analysis of grassland methods demonstrated a potential bias of estimated NPP depending biome type and on which method was used, users are encouraged to review site information to decide which NPP estimates are appropriate for a particular application.

Data Format

The following two files are included in the grasslands NPP data set. Missing or unavailable values are represented by -9999. Variables, units of measure, and example data records are provided below.

File: Grassland NPP_biomass_months (contains 1490 biomass field measurements)

Variable	**Description**
SITE	Unique 3-character site code
TREATMNT	Treatment designation
YEAR	Year of measurement
MONTH	Month of measurement
DAY	Day of measurement
JDATE	Julian day of year
AGBMASS	Aboveground live material
AGTOTCLP	Aboveground total, live + dead
CROWN	Crown (IBP sites), added to agbmass
BGTOTMAT	Belowground total, live + dead
STDEAD	Standing dead material
LITTER	Dead material on ground
BGBMASS	Belowground live root material
BGDEAD	Belowground dead root material
AGTOTMAT	Aboveground total, live + dead

Example data records from the Grassland NPP_biomass_months data file:
SITE,TREATMNT,YEAR,MONTH,DAY,JDATE,AGBMASS,AGTOTCLP,CROWN,BGTOTMAT,
STDEAD,LITTER,BGBMASS,BGDEAD,AGTOTMAT
bcn,lngtrm,1972,3,30,90,67.7,-9999,-9999,-9999,-9999,-9999,-9999,-9999,574.4
bcn,lngtrm,1972,6,2,154,198.4,-9999,-9999,-9999,-9999,-9999,-9999,-9999,570.7

File: Grassland NPP_site_summary (contains location, climate, and vegetation characteristics for 31 sites, along with NPP estimates by five methods).

Variable	Description
Site	Unique 3-character site code
Name	Site name
Country	Country
Rainfall	Mean annual precipitation (mm)
Temperature	Mean annual temperature (°C)
Elevation	Elevation (m)
Latitude	Latitude �?" decimal degrees
Longitude	Longitude �?" decimal degrees
C3_C4	Type of dominant vegetation C3 or C4
Vegetation	Vegetation description
Ecoregion	General ecoregion or biome
ECORGN_Bailey	Specific ecoregion according to Bailey
Reference	Literature citation for site
Start	First year of NPP measurements
End	Last year of NPP measurements
N_years	Number of years
N_trtmt	Number of treatments
Ny_x_Nt	Total number of years and treatments
AGbiomass/litter	Type of aboveground biomass or litter data: Single, Monthly, NA
Bgbiomass	Type of belowground biomass data Single, Monthly, NA
ANPP_lit	ANPP from literature (g /m2/year)
BNPP_lit	BNPP from literature (g /m2/year)
TNPP_lit	TNPP from literature (g /m2/year)
NYR	Number of years used in analysis
MAX_MON	Month with maximum ANPP
ANPP1	ANPP Calculated using Method 1
ANPP2	ANPP Calculated using Method 2
ANPP3	ANPP Calculated using Method 3
ANPP4	ANPP Calculated using Method 4
ANPP5	ANPP Calculated using Method 5
ANPP6	ANPP Calculated using Method 6
BNPP1	BNPP Calculated using Method 1
BNPP2	BNPP Calculated using Method 2
BNPP3	BNPP Calculated using Method 3
BNPP4	BNPP Calculated using Method 4
BNPP5	BNPP Calculated using Method 5
NPP1	NPP Calculated using Method 1
NPP2	NPP Calculated using Method 2
NPP3	NPP Calculated using Method 3
NPP4	NPP Calculated using Method 4
NPP5	NPP Calculated using Method 5

The methods referenced in the Grassland NPP_site_summary. See Table 1 of Scurlock *et al.* 2002 for specific details.

Method	Description
1	Peak live biomass
2	Peak standing crop (live plus standing dead matter)
3	Maximum minus minimum live biomass
4	Sum of positive increments in live biomass
5	Sum of positive increments in live and dead plus litter

Example data records from the Grassland NPP_site_summary data file:
Site,Name,Country,Rainfall,Temperature,Elevation,Latitude,
Longitude,C3_C4,Vegetation,Ecoregion,ECORGN_Bailey,
Reference,Start,End,N_years,N_trtmt,Ny_x_Nt,AGbiomass/litter,
Bgbiomass,ANPP_lit,BNPP_lit,TNPP_lit,NYR,
MAX_MON,ANPP1,
ANPP2,ANPP3,ANPP4,ANPP5,ANPP6,BNPP1,BNPP2,BNPP3,BNPP4,BNPP5,NPP1,
NPP2,NPP3,NPP4,NPP5
bcn,Beacon Hill,U.K.,858,11,205,50.92, -0.85,C3,chalk grassland,Humid temperate,Humid temperate broadleaf
forest(243),Williamson(1976),1972,1973,1,1,1, monthly,N/A,691, -9999,-9999,1,8,355,574,287,287,333,287,
-9999,-9999,-9999,-9999,-9999,-9999,-9999,-9999,-9999,-9999
bdk,Badkhyz,Turkmenistan,310,12.6,700,35.68,62,C3,desert steppe, Temperate dry steppe,Temperate dry steppe (343),
Gilmanov *et al.* (1997),1948,1982,34,1,34,monthly,N/A,100, -9999,-9999,17,5,54,-9999,50,50,-9999,-9999,-9999,
-9999,-9999,-9999,-9999,-9999,-9999,-9999,-9999,-9999

Table 16 NPP Grassland Site Information, Sept. 2001 Field Site Species and Vegetation Type in alphabetical order of species name.

Site	Name	Country	Rainfall	Temperature	Elevation	Latitude	Longitude	C3_C4	Vegetation
mdl	Media Luna	Argentina	338	5.5	630	-45.6	-71.42	C3	grassland steppe
chr	Charleville	Australia	457	19.4	304	-26.4	146.27	C3	semi-arid grassland
mtd	Matador	Canada	350	3	676	50.7	-107.72	C3	mixed grassland
tmg	Tumugi	China	411	2.1	191	46.1	123	C3	meadow steppe
xln	Xilingol	China	361	-2	1200	43.72	116.63	C3	steppe
cns	Cañas	Costa Rica	1926	28	45	10.4	-85.1	C4	derived savanna
lmt	Lamto	Cote d'Ivoire	1165	28.8	300	6.22	-5.03	C4	humid savanna
krk	Kurukshetra	India	688	23.6	247	29.97	76.85	C4	tropical grassland
dzh	Dhzanybek	Kazakhstan	291	5	20	49.33	46.78	C3	semi-desert steppe
shr	Shortandy	Kazakhstan	350	1.3	367	51.67	71	C3	dry steppe
nrb	Nairobi	Kenya	677	19.7	1600	-1.33	36.83	C4	grass savanna
mnt	Montecillo	Mexico	580	14.2	2240	19.46	-98.91	C4	saline grassland
tmn	Tumentsogt	Mongolia	269	1.7	1100	47.4	112.5	C3	typical steppe
krs	Kursk	Russia	594	6.1	250	51.67	36.5	C3	meadow steppe
otr	Otradnoe	Russia	485	8.6	50	60.83	30.25	C3	loamy meadow
tva	Tuva	Russia	285	-4.3	800	51.83	94.42	C3	ultra-continental steppe
nls	Nylsvley	South Africa	666	17.1	1100	-24.65	28.7	C4	broad-leaved savanna
tll	Tullgarnsnaset	Sweden	528	2.5	0	59.2	17.5	C3	shoreline meadow
kln	Klong Hoi Khong	Thailand	1541	26.4	30	6.33	100.93	C4	humid savanna
bdk	Badkhyz	Turkmenistan	310	12.6	700	35.68	62	C3	desert steppe
bcn	Beacon Hill	U.K.	858	11	205	50.92	-0.85	C3	chalk grassland
knz	Konza	U.S.A	859	12.6	400	39.1	-96.61	C4	tallgrass prairie
brd	Bridger	U.S.A.	395	2.7	2340	45.78	-110.78	C3	mountain grassland
ctt	Cottonwood	U.S.A.	400	8.4	744	43.95	-101.87	C3	mixed prairie
cpr	CPER	U.S.A.	334	9.9	1625	40.82	-104.77	C4	shortgrass prairie
dck	Dickinson	U.S.A.	425	4.8	784	46.9	-102.82	C3	mixed prairie
hys	Hays	U.S.A.	564	12.2	714	38.87	-99.38	C4	mixed prairie
jrn	Jornada	U.S.A.	276	14.9	1350	32.6	-106.85	C4	desert grassland
osg	Osage	U.S.A.	1014	15.2	392	36.95	-96.55	C4	tallgrass prairie
khm	Khomutov	Ukraine	424	11.1	75	47.17	38	C3	typical steppe
clb	Calabozo	Venezuela	1252	28.3	98	8.93	-67.42	C4	closed bush island savanna

Site	Name	Country	Ecoregion	ECORGN_Bailey	Reference
mdl	Media Luna	Argentina	Temperate steppe	Temperate dry steppe (331/332)	Defosse *et al.* (1990)
chr	Charleville	Australia	Savanna	Savanna (411/416)	Christie (1978)
mtd	Matador	Canada	Temperate steppe	temperate dry steppe (330)	Coupland (1993)
tmg	Tumugi	China	Cold Steppe	Cold desert steppe (333)	Xiao *et al.* (1996)
xln	Xilingol	China	Cold Steppe	Cold desert steppe (333)	Xiao *et al.* (1995)
cns	Cañas	Costa Rica	Humid savanna	Humid savanna (412)	Daubenmire (1972)
lmt	Lamto	Cote d’Ivoire	Humid savanna	Humid savanna (414)	Menaut and Cesar (1979)
krk	Kurukshetra	India	Humid savanna	Savanna (412)	Singh and Yadava (1974)
dzh	Dhzanybek	Kazakhstan	Temperate steppe	Temperate dry steppe (342)	Gilmanov *et al.* (1997)
shr	Shortandy	Kazakhstan	Cold Steppe	Cold desert steppe (331)	Gilmanov *et al.* (1997)
nrb	Nairobi	Kenya	Savanna	Savanna (413/416)	Kinyamario and Imbamba (1992)
mnt	Montecillo	Mexico	Humid savanna	Forest-meadow-paramo (M421*)	Garcia-Moya and Montanez Castro (1992)
tmn	Tumentsogt	Mongolia	Cold Steppe	Cold desert steppe (333)	Togtohyn *et al.* (1996)
krs	Kursk	Russia	Humid temperate	Humid temperate prairie (252)	Gilmanov *et al.* (1997)
otr	Otradnoe	Russia	Humid temperate	Humid temperate prairie (212)	Gilmanov *et al.* (1997)
tva	Tuva	Russia	Cold Steppe	Cold desert steppe (333)	Gilmanov *et al.* (1997)
nls	Nylsvley	South Africa	Savanna	Savanna (314)	Scholes and Walker (1993)
tll	Tullgarnsnaset	Sweden	Humid temperate	Humid temperate mixed forest (242)	Wallentinus (1973)
kln	Klong Hoi Khong	Thailand	Humid savanna	Humid savanna (423)	Kamnalrut and Evenson (1992)
bdk	Badkhyz	Turkmenistan	Temperate dry steppe	Temperate dry steppe (343)	Gilmanov *et al.* (1997)
bcn	Beacon Hill	U.K.	Humid temperate	Humid temperate broadleaf forest (243)	Williamson (1976)
knz	Konza	U.S.A	Humid temperate	Humid temperate prairie (251/255)	Abrams *et al.* (1986)
brd	Bridger	U.S.A.	Cold Steppe	Alpine meadow steppe (M331)	Sims and Singh (1978)
ctt	Cottonwood	U.S.A.	Temperate dry steppe	Temperate dry steppe (331)	Sims and Singh (1978)
cpr	CPER	U.S.A.	Temperate dry steppe	Temperate dry steppe (311/315)	Lauenroth and Sala (1992)
dck	Dickinson	U.S.A.	Temperate dry steppe	Temperate dry steppe (331)	Sims and Singh (1978)
hys	Hays	U.S.A.	Temperate steppe	Temperate dry steppe/ Humid prairie (332/	Sims and Singh (1978)
jrn	Jornada	U.S.A.	Savanna	Sub-tropical semi-desert (321)	Sims and Singh (1978)
osg	Osage	U.S.A.	Humid temperate	Humid temperate/ subtropical praire (255)	Sims and Singh (1978)
khm	Khomutov	Ukraine	Humid temperate	Humid temperate prairie (332)	Gilmanov *et al.* (1997)
clb	Calabozo	Venezuela	Humid savanna	Humid savanna (414/415)	San Jose and Medina (1976)

Site	Name	Country	Start	End	N_years	N_trtmt	Ny_x_Nt	AGbiomass/litter	Bgbiomass	ANPP_lit	BNPP_lit	TNPP_lit
mdl	Media Luna	Argentina	1981	1983	2	1	2	monthly	N/A	35	-9999	-9999
chr	Charleville	Australia	1973	1974	1	2	2	monthly	monthly	122	60	182
mtd	Matador	Canada	1968	1972	5	2	10	monthly	N/A	431	-9999	-9999
tmg	Tumugi	China	1981	1990	10	3	30	monthly	monthly	155	-9999	-9999
xln	Xilingol	China	1980	1989	10	1	10	monthly	N/A	249	-9999	-9999
cns	Cañas	Costa Rica	1969	1970	1	1	1	monthly	N/A	1387	-9999	-9999
lmt	Lamto	Cote d'Ivoire	1969	1987	8	2	9	monthly	monthly	830	1320	2150
krk	Kurukshetra	India	1970	1971	1	1	1	monthly	monthly	1706	1832	3538
dzh	Dhzanybek	Kazakhstan	1955	1989	33	1	33	monthly	N/A	201	-9999	-9999
shr	Shortandy	Kazakhstan	1975	1978	3	1	3	monthly	monthly	335	1745	2080
nrb	Nairobi	Kenya	1984	1994	8	2	11	monthly	monthly	811	431	1242
mnt	Montecillo	Mexico	1984	1994	11	2	17	monthly	monthly	1063	678	1741
tmn	Tumentsogt	Mongolia	1982	1990	9	1	9	monthly	N/A	160	-9999	-9999
krs	Kursk	Russia	1954	1983	29	1	29	monthly	monthly	774	1700	2474
otr	Otradnoe	Russia	1969	1973	4	2	8	monthly	monthly	306	650	956
tva	Tuva	Russia	1978	1985	6	1	6	monthly	monthly	150	-9999	-9999
nls	Nylsvley	South Africa	1974	1989	4	1	4	monthly	monthly	76	-9999	-9999
tll	Tullgarnsnaset	Sweden	1968	1969	1	2	2	monthly	N/A	430	-9999	-9999
kln	Klong Hoi Khong	Thailand	1984	1990	6	2	7	monthly	monthly	1595	625	2220
bdk	Badkhyz	Turkmenistan	1948	1982	34	1	34	monthly	N/A	100	-9999	-9999
bcn	Beacon Hill	U.K.	1972	1973	1	1	1	monthly	N/A	691	-9999	-9999
knz	Konza	U.S.A	1976	1990	14	1	14	monthly	N/A	394	-9999	-9999
brd	Bridger	U.S.A.	1970	1972	2	2	4	monthly	monthly	249	471	720
ctt	Cottonwood	U.S.A.	1970	1972	3	2	6	bi-weekly	N/A	249	547	796
cpr	CPER	U.S.A.	1939	1990	51	5	75	monthly	N/A	172	568	740
dck	Dickinson	U.S.A.	1970	1970	1	2	2	monthly	monthly	351	932	1283
hys	Hays	U.S.A.	1970	1970	1	2	2	monthly	monthly	363	1062	1425
jrn	Jornada	U.S.A.	1970	1972	3	2	6	monthly	monthly	148	147	295
osg	Osage	U.S.A.	1970	1972	3	2	6	monthly	monthly	346	542	887
khm	Khomutov	Ukraine	1967	1970	4	1	4	monthly	N/A	460	-9999	-9999
clb	Calabozo	Venezuela	1969	1987	2	2	4	monthly	single	375	307	682

Site	Name	Country	NYR	MAX_MON	ANPP1	ANPP2	ANPP3	ANPP4	ANPP5	ANPP6	BNPP1	BNPP2	BNPP3	BNPP4
mdl	Media Luna	Argentina	2	7	34	282	19	15	75	64	-9999	-9999	-9999	-9999
chr	Charleville	Australia	1	2	120	-9999	116	114	-9999	-9999	-9999	95	-9999	-9999
mtd	Matador	Canada	5	7	131	560	109	109	600	246	-9999	-9999	-9999	-9999
tmg	Tumugi	China	10	9	152	-9999	149	151	-9999	-9999	979	-9999	119	113
xln	Xilingol	China	7	8	174	-9999	159	157	-9999	-9999	-9999	-9999	-9999	-9999
cns	Cañas	Costa Rica	2	6	472	-9999	400	258	-9999	-9999	-9999	-9999	-9999	-9999
lmt	Lamto	Cote d'Ivoire	8	6	446	389	308	295	411	404	-9999	1499	-9999	-9999
krk	Kurukshetra	India	2	7	1387	1692	1241	1075	1255	1173	-9999	671	-9999	-9999
dzh	Dhzanybek	Kazakhstan	5	6	149	-9999	139	185	-9999	-9999	-9999	-9999	-9999	-9999
shr	Shortandy	Kazakhstan	3	6	138	297	123	109	249	141	2514	3387	1333	1415
nrb	Nairobi	Kenya	10	6	237	638	172	202	488	419	225	298	168	161
mnt	Montecillo	Mexico	10	9	304	705	269	281	609	281	619	1229	332	553
tmn	Tumentsogt	Mongolia	9	8	174	-9999	105	118	-9999	-9999	-9999	-9999	-9999	-9999
krs	Kursk	Russia	29	7	372	652	339	329	671	507	1426	2438	748	784
otr	Otradnoe	Russia	4	7	244	294	233	234	292	296	636	701	266	269
tva	Tuva	Russia	2	7	123	152	109	144	147	151	610	-9999	0	-9999
nls	Nylsvley	South Africa	4	4	87	-9999	63	40	-9999	-9999	-9999	-9999	-9999	-9999
tll	Tullgarnsnaset	Sweden	1	7	296	339	282	251	361	293	-9999	-9999	-9999	-9999
kln	Klong Hoi Khong	Thailand	6	8	353	612	228	304	610	604	784	746	450	518
bdk	Badkhyz	Turkmenistan	17	5	54	-9999	50	50	-9999	-9999	-9999	-9999	-9999	-9999
bcn	Beacon Hill	U.K.	1	8	355	574	287	287	333	287	-9999	-9999	-9999	-9999
knz	Konza	U.S.A	7	8	327	-9999	260	300	-9999	-9999	-9999	-9999	-9999	-9999
brd	Bridger	U.S.A.	2	8	223	232	134	134	138	136	-9999	-9999	-9999	-9999
ctt	Cottonwood	U.S.A.	3	6	188	246	182	203	362	265	-9999	-9999	-9999	-9999
cpr	CPER	U.S.A.	3	7	198	192	102	172	216	172	-9999	-9999	-9999	-9999
dck	Dickinson	U.S.A.	1	9	270	366	233	264	503	502	-9999	-9999	-9999	-9999
hys	Hays	U.S.A.	1	7	225	225	225	235	436	319	-9999	-9999	-9999	-9999
jrn	Jornada	U.S.A.	3	9	103	104	96	111	168	137	-9999	138	-9999	-9999
osg	Osage	U.S.A.	3	7	287	429	285	293	540	456	-9999	506	-9999	-9999
khm	Khomutov	Ukraine	4	6	366	429	366	295	330	371	-9999	-9999	-9999	-9999
clb	Calabozo	Venezuela	2	8	309	1125	278	278	1121	313	-9999	291	-9999	-9999

Site	Name	Country	BNPP5	NPP1	NPP2	NPP3	NPP4	NPP5
mdl	Media Luna	Argentina	-9999	-9999	-9999	-9999	-9999	-9999
chr	Charleville	Australia	-9999	-9999	-9999	-9999	-9999	-9999
mtd	Matador	Canada	-9999	-9999	-9999	-9999	-9999	-9999
tmg	Tumugi	China	-9999	1130	-9999	269	275	-9999
xln	Xilingol	China	-9999	-9999	-9999	-9999	-9999	-9999
cns	Cañas	Costa Rica	-9999	-9999	-9999	-9999	-9999	-9999
lmt	Lamto	Cote d'Ivoire	-9999	-9999	1942	-9999	-9999	-9999
krk	Kurukshetra	India	-9999	-9999	2363	-9999	-9999	-9999
dzh	Dhzanybek	Kazakhstan	-9999	-9999	-9999	-9999	-9999	-9999
shr	Shortandy	Kazakhstan	1783	2652	3684	1456	1524	2032
nrb	Nairobi	Kenya	362	462	921	340	363	850
mnt	Montecillo	Mexico	1211	934	1961	607	844	1783
tmn	Tumentsogt	Mongolia	-9999	-9999	-9999	-9999	-9999	-9999
krs	Kursk	Russia	1281	1958	3291	1230	1231	1995
otr	Otradnoe	Russia	410	881	995	500	503	702
tva	Tuva	Russia	-9999	733	-9999	109	-9999	-9999
nls	Nylsvley	South Africa	-9999	-9999	-9999	-9999	-9999	-9999
tll	Tullgarnsnaset	Sweden	-9999	-9999	-9999	-9999	-9999	-9999
kln	Klong Hoi Khong	Thailand	670	1137	1358	678	822	1280
bdk	Badkhyz	Turkmenistan	-9999	-9999	-9999	-9999	-9999	-9999
bcn	Beacon Hill	U.K.	-9999	-9999	-9999	-9999	-9999	-9999
knz	Konza	U.S.A	-9999	-9999	-9999	-9999	-9999	-9999
brd	Bridger	U.S.A.	-9999	-9999	-9999	-9999	-9999	-9999
ctt	Cottonwood	U.S.A.	-9999	-9999	-9999	-9999	-9999	-9999
cpr	CPER	U.S.A.	-9999	-9999	-9999	-9999	-9999	-9999
dck	Dickinson	U.S.A.	-9999	-9999	-9999	-9999	-9999	-9999
hys	Hays	U.S.A.	-9999	-9999	-9999	-9999	-9999	-9999
jrn	Jornada	U.S.A.	-9999	-9999	230	-9999	-9999	-9999
osg	Osage	U.S.A.	-9999	-9999	974	-9999	-9999	-9999
khm	Khomutov	Ukraine	-9999	-9999	-9999	-9999	-9999	-9999
clb	Calabozo	Venezuela	-9999	-9999	-9999	-9999	-9999	-9999

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