Methods to estimate grassland production and biological fixation

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Lot 2. Grassland areas, production and use

Current methods to estimate grassland production and biological fixation

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Summary

The estimates of grassland production have a large effect on the nutrient balance of pasture based livestock systems. Furthermore, estimates of biological nitrogen fixation of mixed legume-grass swards are not included in current nutrient balances. The objective of this study was to bring clarity into the issue of collecting data on existing methodologies to estimate grassland production and biological fixation in European grasslands.

The potential production level of grasslands is determined by the interception of the photosynthetically active radiation, the radiation use efficiency, the length of the growing season, and the partitioning of plant mass. Each of the above processes are sensitive to environmental stress which will result in an inability to attain maximum yields. Inadequate water and nutrient supplies are the most common factor for lower yields, but other environmental and management are relevant as well.

Most grassland used for agricultural purposes is stocked by animals for at least part of the time and in many cases year-long. Grazing affects grassland production because of defoliation, treading and fouling. Harvesting and grazing take place frequently or at least several times in a year. For these reasons measuring yield of forage is more difficult than that of other crops. The methods for determining grassland production can be classified in destructive (cutting) and non-destructive (visual estimates, grass height measurements and remote sensing), and modeling. Destructive measurement is commonly applied on grassland experiments throughout Europe. Although non-destructive methods are less accurate on a per sample basis than cutting methods, they take less time per observation and involve less physical effort by the operators. The larger number of observations offers more opportunity for examining spatial and temporal heterogeneity. Remote sensing offers a potential alternative to for monitoring vegetation condition and estimating productivity over large areas of grasslands. Research has mostly focused on the use of high spatial resolution satellite imagery on behalf of crop modeling. Although results demonstrated that many crop model states could be improved using satellite observations, such methods have proven difficult to be applied in crop yield forecasting applications operating at regional to continental scales. The main reason for this slow adoption is the disparity in scales between the process and the type of observing system.

There is a wide variety in modeling approaches of grassland production. In this study we distinguish mechanical process based models and empirical models. As a special case of empirical models we consider the feed balance approach. For purposes of farming systems research and collection of statistical data on regional levels, feed balances are often used to estimate grassland production. Feed balances are calculated with data on feed availability for ruminants and their feed requirements.

Table 1 Overview of grass production assessment methods

Method	Scale	Gross production	Net production	Net feed intake
Cutting and weighing	plot, field, farm	x	x	
Height and density measurement	plot, field	x		
Visual estimate	plot, field, farm	x	x	
Modeling	plot, field, farm, region	x	x	x
Remote sensing	region	x		
Feed balance	farm, region			x

Measurement of nutrient contents in grassland is also categorised in destructive (sampling and analyzing) and non-destructive (chlorophyll, near infrared reflectance spectrometry). Strong correlations exist between data from satellite imagery and the concentration of many biochemicals within vegetation canopies.

Nitrogen-fixing legumes are significant components of many agricultural systems, and nodulated legumes contribute the majority of the biologically-fixed nitrogen supplied to both temperate and tropical agricultural systems. This study focuses on nitrogen fixation in plant associated pastures and fodder crops, i.e. the mutualistic interaction between rhizobia and legumes. The amount of N fixed by clover is difficult to estimate, because both the estimate of the average share of clover in grassland in a region and the amount of N fixed by clover are uncertain. If clover is grown on soils that contain mineral N (e.g. because of N fertilizer or manure application), clover can use this N and may not or slightly fix atmospheric N. In that case, not all N of the clover should be included in the gross N balance calculations. There are many techniques available for the direct quantitative measurement of legume BNF in the field. However, these are time-consuming and therefore expensive, and generate data relevant only to the time and place of measurement. Alternatively, legume BNF can be estimated by either empirical models or dynamic mechanistic simulation models.

Member states collect a wide variety of yield data, either directly as yield, or indirectly through volume of grazed grass, volume of cut grass, number of cuts/harvests per year, management intensity, grazing status, grazing intensity, nitrogen input levels as fertiliser or manure, and proportion of clover or other N fixing plants. The methods used to estimate grassland production are very heterogeneous. Most members states use expert estimates, while destructive measurements are also mentioned frequently. Less frequently mentioned methods involve default values from literature, non-destructive measurements, calculations of a crop growth model and estimates using feed balance calculation.
With respect to nutrient contents, members states mainly use derived values from literature or direct measurements in samples of harvested grass.
Data on biological nitrogen fixation are usually not collected. Those member states that do, mostly rely on values retrieved from literature in combination with expert estimates. Measurements and models are not mentioned frequently.

We suggest a tiered approach including fixed, modeled or measured values for each of the three parameters.

Fixed estimates are those values that are derived from literature research in combination with expert opinions. Sources are preferably peer reviewed papers, but data from other sources may be used as well. Often data availability is limited with white spots for certain areas or periods. Regional and national grassland experts are a valuable resource for completing these missing data. Data availability will decrease in the order yield > nutrient content > fixation, but in all cases the framework of the approach is similar.

Modeled estimates comprise a wide range of empirical or mechanistic approaches of estimating yields, nutrient content or biological fixation, with varying complexity. Models are preferably published and peer reviewed and calibrated and validated on local conditions. Again in this category, models for yield estimates are developed abundantly, compared to models for nitrogen fixation. With respect to yield estimates, the use of feed balances has been applied in several countries and may serve as a template for other member states. Less experience is available for nitrogen fixation. Whichever modeled approach is chosen, the most important underlying factors, proportion of legumes in the sward and applied nitrogen, should be considered.

Measured estimates are those values derived from *in situ* measurements of yields, nutrient contents of nitrogen fixation. Although the direct measurement is in theory the best proxy, the methods has similar pitfalls as the lower tier methods with respect to upscaling from a local site at a specific time to higher spatial and temporal scales. Furthermore it has to be clear that on experimental sites potential yields are measured such as in the grassland network used in the 1980's (Corrall, 1988; Peeters & Kopec, 1996). Potential yields are significantly higher than those obtained under commercial farming conditions. Therefore, measurement networks should preferably be located at commercial farms, on plots used for grazing as well.

Table 2 Framework for three tiered approach.

	Fixed estimate	Models	Measurements
Sources	• Literature • Experts	• Calibrated and validated model • Meteorological data • Farm management data • Statistical farm data • Feed requirements • Data on imported feed • Data on legume contents in swards	• Network of experimental plots • Network of commercial (pilot) farms
Temporal scale	• Annual	• Seasonal • Annual	• Seasonal • Annual
Spatial scale	• Regional • National	• Regional • National	• Regional • National
Uncertainties and risks	• Expert bias • Incomplete spatial coverage of data	• Availability of data for calibration and validation • Feed balances require many additional data on livestock and external feed inputs and quality	• Overestimation of actual yields • Availability of representative monitoring network
Relative costs	• Low	• Medium	• High

In the Tier 1 method, estimates of grassland yields and nutrient contents should be made on a preferably NUTS II level, or for smaller member states at national level, and annual basis. This has to be done for the grasslands categories that are relevant for nutrient balances (Table 19).

Table 3 Proposal for a table to be used in a Tier 1 approach for estimates of dry matter yields, N and P contents of grassland, for different hypothetical grassland classes and regions in EU.

	Region/member state					
Grassland category	1	2	3	4	5	etc.
A						
B						
C						
D						
etc.						

The data required for the Tier 2 (modelling including feed balances) and Tier 3 (measurements) methods strongly depend on the approach that will be used. No general recommendations can be made for data collection using Tier 2 and 3.

1 Introduction

1.1 Background

Grasslands are an important land use in Europe covering more than a third of the European agricultural area. Grasslands have a basic role in feeding herbivores and ruminants and provide important ecosystem services, including erosion control, water management and water purification. Grasslands also support biodiversity and cultural services, e.g. recreational values, and are an important stock of carbon (Smit et al., 2008).

Grasslands are very diverse in terms of management, yield and biodiversity value. They range from semi-natural grasslands with low yields and high biodiversity values to fertilised mono-cultural grasslands. Most of the grass in the EU originates from intensively managed grasslands, stimulated by fertiliser application. Extensive, high nature value grasslands have low yields. Examples of such areas are mountain summer grazing areas, semi-natural grasslands and other areas used for extensive grazing.

Accurate data on grassland area, grassland production and nutrient contents are very important for calculation of gross nutrient balances in the EU and other agri-environmental indicators (e.g. greenhouse gas emissions) and policies (e.g. CAP reform, Nitrates Directive). This requires well-defined characterization of the grassland types, management of these grasslands and the productivity (both in terms of biomass and nutrients).

Part of the natural and extensively used grasslands are not important from a nutrient perspective, because there is no input of nutrients and, by that, no or limited emissions to the environment. A gross nutrient balance expressed on basis of a hectare agriculture land should not include these types of grassland, as these balances are used for indicating the pressure on the environment by nutrients from agriculture. Including extensively used managed grasslands in these calculations may mimic high nutrient pressures on the environment. The definitions and characterization should be used in an uniform and harmonized way in the EU-27 so that the same information is gathered in the different member states. Such an uniform approach is needed to derive gross nutrient balances (and other agri-environmental indicators) based on the same methodology and type of data.

1.2 Objectives

The objective of this study for Eurostat[1] is to bring clarity into the issue of defining, classifying, collecting and disseminating data on European grassland areas, use and production. The specific aim of this report is to make a literature review on existing methodologies to estimate grassland production and to estimate biological fixation in grasslands.

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[1] Methodological studies in the field of Agro-Environmental Indicators (2012/S 87-142068) Lot 2. Grassland areas, production and use

1.3 Outline report

According to the proposal this study will deliver the following outputs, which have been integrated in this report:

- A document reviewing the various methodologies used to estimate grassland production and biological fixation in grasslands.
- Guidelines for methods to estimate grassland production both in biomass and nitrogen.

Chapter 2 presents an overview on the theoretical basis of grass production and measurement and modelling techniques to estimate yields and nutrient contents. Chapter 3 describes the nitrogen fixation process and measurement and modelling techniques to estimate biological nitrogen fixation. Chapter 4 reviews the current methods used in member states to estimate national production of grassland and biological fixation in grasslands. Finally Chapter 5 will conclude with recommendations to estimate grassland yields.

2 Grassland production

2.1 Theoretical basis of grass production

Agricultural ecosystems collect solar energy and store it as chemical energy in the form of carbohydrates, lipids and proteins. The interception of solar radiation and its use to accumulate plant biomass can be described by four processes (Sinclair and Weiss, 2010).

1) Interception of the photosynthetically active radiation.
About half the energy in solar radiation is photosynthetically active radiation (PAR). The fraction of PAR intercepted by a canopy is dependent on the extent of the leaf area index (LAI), which is the ratio of the leaf surface area (one side) per unit ground surface area. For many established crops in agricultural systems, the LAI is roughly 4 to 6. In grass swards, the LAI may range from zero at sowing to nine for a full grown crop (Simon and Lemaire, 1987). At an LAI of 1.0, approximately 50% of PAR is intercepted, 90% at an LAI of 3.3 and 95% at an LAI of 4.3. Factors promoting a rapid development of LAI are adequate supply of water and nutrients, a vigorously growing genotype, adequate plant density and an optimal spatial arrangement of plants.

2) Radiation use efficiency
Intercepted PAR is absorbed by leave pigments, mainly chlorophyll, and used to produce chemical energy in the plant. The energy is transferred in several steps to energy-rich intermediates adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH). In turn ATP and NADPH provide the energy to assimilate carbon dioxide (CO2) into simple organic molecules. Most plants, identified as C3 species, produce three-carbon sugars as building blocks for other compounds. In another group of plants, identified as C4 species, the initial CO2 capture is in four-carbon organic acids. These acids are transported to specialized cells where CO2 is released again and processed further as in C3 plants. It is common to refer to C3 grasses as temperate grasses and C4 grasses as tropical grasses, despite the distinction being less clear cut (Jones and Lanzenby, 1988).
The amount of assimilated CO2 is a function of the amount of PAR energy stored in ATP and NADPH. Therefore the amount of dry matter produced is directly related to the amount of absorbed radiation. The radiation use efficiency (RUE) is defined as the accumulated plant mass per unit of intercepted radiation. An important factor for RUE is the photosynthetic capacity of the individual leaves: a high capacity leads to high dry matter accumulation, but with diminishing slope. Furthermore RUE depends on the plant composition. Carbohydrates require less energy than proteins or lipids. Therefore, plants with high protein or lipid content have lower RUE's. For instance, one gram of photosynthate is required for 0.71 gram of wheat, compared to 0.43 gram of rape.

3) Length of growing season.
The total mass accumulated in plants during a growing season is derived from the sum of the daily biomass growth values, which is the product of intercepted radiation and RUE. The daily values of radiation are dependent on location (latitude, elevation, and topography) but also on short term weather variability. For grasslands, the amount of intercepted radiation shows more changes due to the harvest sequence throughout the season. After cutting or grazing there must be sufficient regrowth to achieve an LAI to again intercept high amounts of radiation. The RUE is relatively stable for much of the growing season. However, it has been found to decrease during the latter stages of seed growth. Transfer of nitrogen from the vegetative components such as leaves leads to a sequence of events that result in decreasing LAI and RUE during reproduction.

Temperature is the most critical factor for the length of the growing season. Average temperatures of 5^{0}C are often used as a rule of thumb for crop growth.

4) Partitioning of plant mass.
The yield is generally determined by the fraction of the total plant mass that is harvested. The harvest index (HI) of grasses is defined as the harvestable biomass divided by the total above ground biomass. The HI of forage grasses depends on the residual biomass (stubble) left after cutting or grazing. The HI generally is around 0.7 to 0.8 (Larcher, 2003; Jing et al., 2011).

Each of the above processes are sensitive to environmental stress which will result in an inability to attain maximum yields. Inadequate water and nutrient supplies are the most common factor for lower yields, but other factors such as extreme temperatures, pathogens or competition with weeds may be relevant as well.

2.1.1 From light energy to net feed intake

Only a small fraction of the light energy is converted to harvestable dry matter (Table 4, Figure 1). Approximately 47% of energy in sunlight is intercepted by the grass canopy, of which 90% is lost through transpiration. This leaves approximately 5% of the light energy available for gross photosynthesis, which is theoretically equivalent to 50 t of DM/ha/year. Nearly half the energy is lost through respiration, leaving a net photosynthesis for plant growth of approximately 27.5 t DM/ha/year. After deducting root growth and litter and stubble losses, a gross grass production remains of approximately 13.8 t DM/ha/year. This is equivalent to 1.4% of the total light energy or 28% of gross photosynthesis.

Table 4 Partitioning of energy and biomass; from light energy to net feed intake (modified from Sibma and Ennik, 1988).

	Proportion (%)	Energy (MJ/m2/year)	Biomass (t DM/ha/year)
Light energy	100	1735	
- Outside growing season	28	486	
During growing season	72	1249	
- Bare soil	22	382	
On grass canopy	50	868	
- Reflection	3	52	
Absorbed	47	815	
- Transpiration	42	729	
Gross photosynthesis	5	87	50.0
- Respiration	2.3	39	22.5
Total plant growth	2.8	48	27.5
- Root growth	0.6	10	5.5
Above ground biomass	2.2	38	22.0
- Litter and stubble losses	0.8	14	8.3
Gross grass production	1.4	24	13.8
- Harvest and grazing losses	0.3	4	2.5
Net grass production	1.1	20	11.3
- Conservation and feeding losses	0.1	1	0.5
Net feed intake	1.1	19	10.8

When assessing grassland production it is important to know whether gross grass production, net grass production or net feed intake was measured. Losses during harvest, grazing, conservation and feeding are variable, depending on the management system. In the example from Sibma and Ennik (1988), net grass production is 82% of gross grass production and net feed intake is 78% of gross grass production.

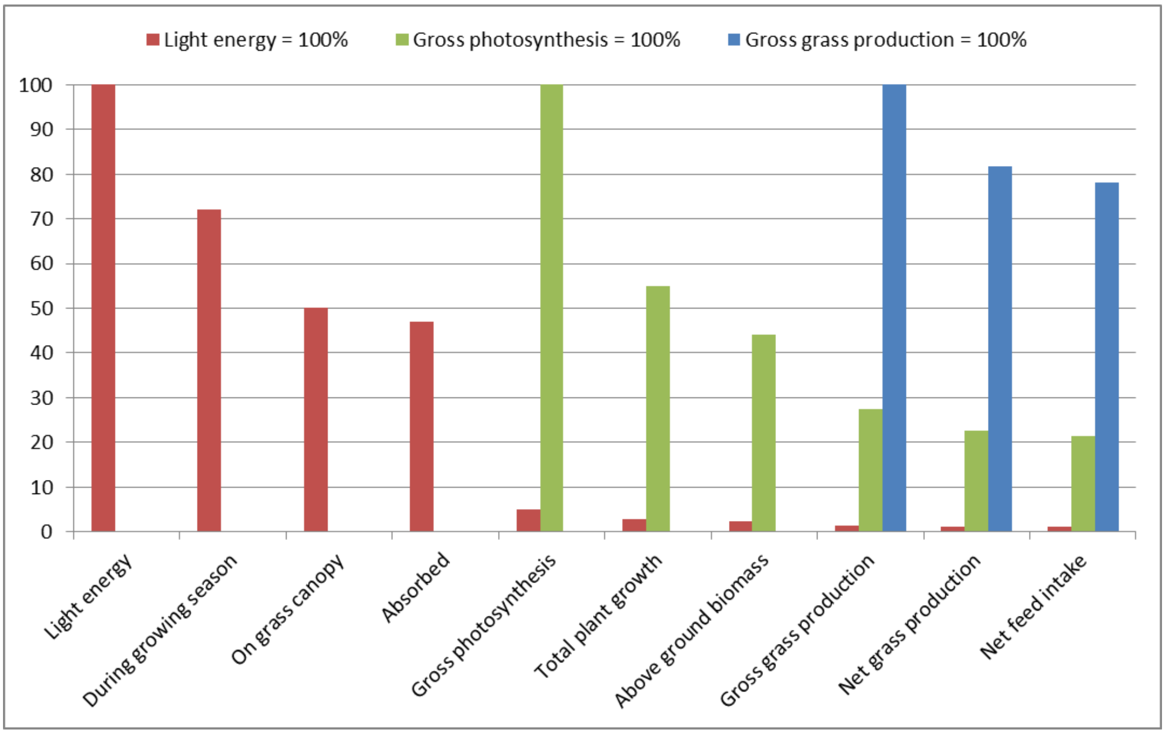

Figure 1 Partitioning of energy; from light energy to net feed intake (modified from Sibma and Ennik, 1988).

2.2 Measurement of grass production

Most grassland used for agricultural purposes is stocked by animals for at least part of the time and in many cases year-long. Grazing affects grassland production because of defoliation, treading and fouling. Much of the grazing takes place in the growing season and that makes forage exceptional as an agricultural commodity: it is harvested whilst it grows and the harvestable product is at the same time the photosynthetic material that produces it. Harvesting takes place frequently or at least several times in a year. For these reasons measuring yield of forage is more difficult than that of other crops ('t Mannetje, 2000).

In intensive animal production systems, grassland yield, although initially sampled as DM or OM, is often expressed in terms of feeding units based on net energy value. Several systems are in use (Van der Honing, 1998), e.g. VEM ('fodder units milk') or VEVI ('fodder units intensive beef production') in The Netherlands, ME ('metabolizable energy') in the UK, and UF ('unité fourragère') in France. In the USA and many Latin American countries the TDN ('total digestible nutrient') system is used, which is based on digestible energy. In some countries the original SE ('starch equivalent') is still in use.

2.2.1 Destructive measurement

Biomass of grassland vegetation refers to above-ground herbaceous material, commonly referred to as 'dry matter (DM) yield'. Research workers and managers of grassland vegetation are interested in this to determine the amount of available forage for animals or to measure the effects of management on the vegetation. Vegetation biomass is important also for assessment of grassland or rangeland condition and for evaluation of new germplasm and cultivars ('t Mannetje, 2000). The value of measuring standing forage may be enhanced by measurements of nutritive value (see 2.3). Forage can be divided into botanical species, into groups of species (grasses, legumes, weeds or other species), or into standing green and dead material and litter. The quantity of grassland vegetation present at any one time can be used to calculate changes, such as herbage growth, utilization by grazing animals, or deterioration. Although the basic techniques of measuring the amount of vegetation present can be used for each of these purposes, the procedures and intensity of sampling will differ depending on the objectives of the measurements.

The simplest devices are hand-operated tools, such as scissors, shears, secateurs, sickles, knives and scythes. Small hand-held tools are useful for small plots when the material is to be divided into species or groups of species. Engine-driven reciprocating cutter bar mowers and lawn mowers with a catcher can be used in short to medium tall swards. A commonly used Danish harvester (Haldrup) has a cutting width of 1.5 m, with adjustable stubble height. The total fresh weight is automatically recorded for each plot. A sample of the cut material is taken by hand, or automatically in new models.

It is essential with any type of cutting implement that cutting height above ground level can be controlled. Hand-held shears or secateurs can cut to near ground level. However, this may affect regrowth and sampling areas cut to ground level should be omitted from sampling again in the near future. Cutting heights will vary depending on the type of grassland, ranging from 1 cm in closely grazed pastures to 10–20 cm in tall swards. In many experiments, grasslands are cut at 4 to 5 cm. Low cutting heights and mechanized equipment can suck in extraneous material such as detached litter, twigs, gravel and dry faeces. Such equipment can generally not be used in stony areas.

Instead of DM yield, vegetation mass can also be expressed as organic matter (OM). OM yield has the advantage that it is true herbage yield without soil contamination, which often occurs in herbage samples as a result of mechanical cutting, raking up of grass or rain splash. Contamination increases weight and distorts chemical analyses. Where samples have to be used for mineral analysis, care needs to be taken to avoid contamination of the samples, or to clean the material beforehand with minimum losses of minerals. If contamination is unavoidable, the cut material should not be used for chemical analyses, but separate pluck samples should be taken for that purpose. However, plucked samples can still be contaminated by soil from rain splash.

Destructive measurement is commonly applied on grassland experiments throughout Europe, e.g. to establish response curves to fertilizer application (Figure 2).

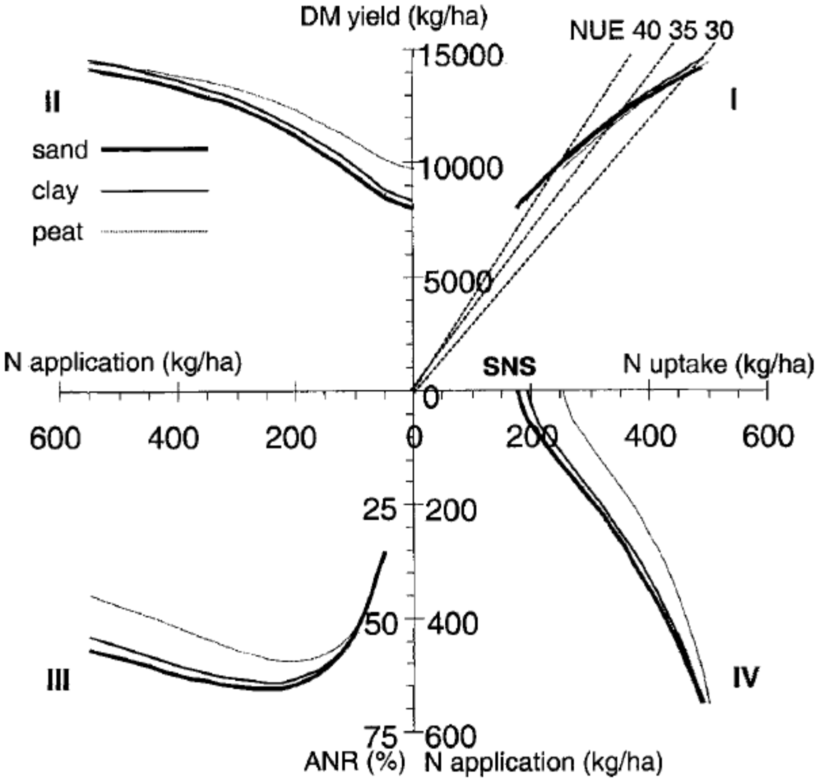

Figure 3. Mean effects of N fertiliser application on N uptake (quadrant IV), DM yield (quadrant II), ANR (quadrant III) and NUE (quadrant I) as a function of soil type (sand, clay and peat). Mean relationships are based on the whole 'sixty-year' dataset of nitrogen fertiliser experiments.

Figure 2 Mean effects of N fertiliser application on N uptake (IV), DM yield (II), ANR (III) and NUE (I) as a function of soil type. Mean relationships are based on the sixty-year dataset of nitrogen fertiliser experiments (Vellinga and André, 1999).

2.2.2 Non-destructive measurement

Destructive sampling requires high inputs of labour and/or equipment. This can be costly and may lead to insufficient sample numbers, resulting in low precision. Destructive sampling also prevents measuring changes of the sward in the sampling area. In small grazed plots the material removed by cutting may be a significant proportion of the feed available. For these reasons, non-destructive sampling techniques have been developed, which can be grouped into three categories: (i) visual estimation; (ii) height and density measurements; and (iii) measurement of non-vegetative attributes that can be related to DM yield.

Although non-destructive methods are less accurate on a per sample basis than cutting methods, they take less time per observation and involve less physical effort by the operators. Thus, when compared with destructive techniques, DM yields may be estimated more accurately even though the yield of each quadrat is measured less accurately. The larger number of quadrats also offers more opportunity for examining spatial heterogeneity (McDonald and Jones, 1997).

The non-destructive methods in use are often double sampling techniques, i.e. two overlapping methods are used. One is an accurate determination of DM yield in a few samples (standards) and the other is a visual estimate, height or capacitance reading of herbage in many samples, including the standards. Regression equations between the estimated non-yield parameter and DM yield of the standards provide the calibration of the technique. Therefore, non-destructive techniques still require some sample cutting, but the amount to be cut is small and, if necessary, cutting can be restricted to an area of the same sward that is outside the measurement or treatment area.

Visual assessment
Although experienced operators who are very familiar with the type of pasture under consideration may be able to estimate the amount of DM present in a field to within circa one t/ha, without any calibration cuts, the procedure is of limited value research. It is less complicated for monospecific swards or very simple mixtures.

The comparative yield method (CYM) (Haydock and Shaw, 1975) has been widely used. With the CYM, standards are selected covering the range of DM yield usually on a scale of 1 (lowest) to 5 (highest). The area is then sampled using many quadrats, with yields estimated to 0.1 units on the same 1–5 scale. Within any one quadrat it is often easier to estimate DM yield in terms relative to a set of standards than to estimate DM yield in absolute terms. When sampling is completed, a new set of at least ten quadrats, spanning the range of yields, is set out. These are estimated independently by each operator and then cut, dried and weighed. The regression equations derived from the standards are then used to calculate the dry matter yields of the paddock samples. Although Haydock and Shaw (1975) reported correlation coefficients of estimated values of DM obtained by CYM and by hand cutting of 0.98–1.00, it is more usual to find values between 0.90 and 0.98.

Height and density
The standing biomass of an area of grassland is related to the density and height of its individual components. Height and density measurements of a sward can be integrated using a 'weighted disc', 'rising plate', 'drop-disc', or 'pasture disc', of which there are many types in use. They consist of a round or square disc of light metal or of plastic foam of a given weight that can slide along a central rod, which is lowered or dropped from a fixed height on to the sward. In The Netherlands, a round plastic foam disc of 50 cm diameter, weighing 340 g, exerting a pressure of 1.7 kg/m2, is commonly used. A widely used implement in Europe is the HFRO sward stick (Barthram, 1986; Stewart et al., 2001), which measures plant height rather than compressed sward height. It employs a 2 × 1 cm clear window that is lowered vertically on a shaft until its base touches the vegetation. The height contact above the ground is recorded in 0.5 cm bands.
The weighted disc and the HFRO sward stick methods are very useful on short pastures, being frequently used on L. perenne and T. repens pastures. Neither method should be used in very tall or lodged grass, and they are less accurate with stemmy material. The calibration of height and DM yield needs to be established for each type of pasture under study, or before every sampling event when the structure of the herbage changes.

The principle of capacitance meters is based on a signal produced by an oscillator in an electrical circuit, which changes as the capacitance under the measuring head changes. Herbage mass has a high capacitance whereas that of air and wood is very low. The difference in capacitance between a quadrat on bare ground and on a grass sward is an indirect method to measure DM yield. Capacitance meters have been used since 1956 and although improved versions have been developed, their performance still leaves much to be desired, except under the special circumstances. The meters need to be calibrated before each sampling occasion, because the capacitance values depend on the species and the moisture content. Vickery et al. (1980) and Vickery and Nicol (1982) have claimed that their single-probe meter, from which the New Zealand 'pasture probe' has been developed, is responsive to surface area of herbage DM and less sensitive to variation in moisture content of the sward.

2.2.3 Remote sensing

General

Remote sensing is the science of obtaining information about an object, an area, or phenomenon through the analysis of data acquired by a sensor that is not in contact with the object, area or phenomenon under investigation (Lillesand et al., 2008). The relevance of remote sensing as a source of information for grasslands is conditioned by the following sensor characteristics:

- spatial resolution – determines the amount of information in a remotely sensed image of a given area;
- spectral resolution – helps to distinguish between plants of different species;
- temporal resolution – allows an improvement in the identification of grassland associations.

Remote sensing has proven to be an important tool for monitoring land cover classes, including grasslands. Nevertheless, the distinction of grassland types can only be improved by better understanding and description of these habitat types in terms of their spectral signatures and their spatial and temporal variation, next to the description of textural features (tone, texture, structure and patterns) of the different types of satellite imagery (e.g. Landsat TM, IKONOS) depicting the grasslands. Recently the use of LiDAR (Laser altimetry) plays an important role in the distinction of vegetation structure. A particular advantage of using spaceborne over airborne data is that greater coverage in one data-take and consistency in the imagery across the landscape are provided, particularly as image strips from airborne data often need to be combined. For some habitats, such as those dominated by forbs (e.g., bracken; *Pteridium aquilinum*) or which contain a diverse mix of species (e.g., active bogs with a mix of shrubs, forbs, graminoids and lichens), information on the distribution and/ relative amounts (e.g., in terms of cover) of particular plant species is required. For non-life forms, spatial information on surface materials (e.g., sand, mud) and water characteristics (e.g., sediment load) is needed. When single-date multi-spectral data (typically visible blue, green and red and near infrared; NIR) are used for this purpose, capacity for discrimination is hampered because of correlations between bands, the limited dynamic range (quantization levels) and the broad spectral range in the channels provided. For example, the launch of the Worldview-2 (WV-2) with a spatial resolution of 2 meters and eight spectral bands has provided new opportunities for discrimination of land covers/habitats. Nevertheless, single-date imagery is still limited for the level of classification detail required.

Hyper-spectral sensors offer finer spectral measurements than multi-spectral instruments, with often hundreds of spectral bands of narrow (e.g.. 0.1 nm) width allowing a near continuous spectrum to be generated for each pixel. This presents opportunities for more precise identification of surface materials compared to when broadband multispectral sensors are used. In the spectral region, these sensors can record reflectance from the visible blue through to the shortwave infrared (SWIR) wavelength regions. For example, APEX is an advanced scientific instrument for the European remote sensing community, recording hyper-spectral data in approximately 300 bands in the wavelength range between 400 nm and 2500 nm and at a spatial ground resolution of 2 m to 5 m. Others include the HYMAP and Airborne Visible Infrared Imaging Spectrometry (AVIRIS) and the Multi-spectral Infrared and Visible Imaging Spectrometer (MIVIS), with the latter extending into the thermal infrared. Whilst airborne sensors have acquired the majority of hyper-spectral data, spaceborne sensors have also operated over the past decade (e.g., HYPERION and CHRIS PROBA). Future sensors are also being constructed for launch in the next five years. Italy's ASI space agency plans to launch Prisma, a medium-resolution hyper-spectral imaging mission, in 2012. Prisma's hyper-spectral camera will be able to acquire images in about 235 channels in the VNIR and SWIR wavelength regions. The German Aerospace Center (DLR) and the German Research Centre for Geosciences (GFZ) are planning to launch the EnMAP hyper-spectral satellite in 2014 to map the Earth's surface in over 200 narrow wavebands. EnMAP is designed to record bio-physical, biochemical and geo-chemical variables to increase understanding of biospheric/geospheric processes (http://www.esa.int). In 2015, NASA plans to launch the HyspIRI mission, which will acquire imagery across 210 spectral bands, with focus on providing information on ecosystems, including the nutrient and water status of vegetation. Thus, spaceborne data are going to become increasingly available by the end of the decade.

Another new development is the use of near-sensing, where sensor systems are placed on tractors and other devices for agricultural management. Currently, sensor technology is adopted to support decision making and assist farmer in timing of production practises, such as irrigation or plant protection or in allocating chemicals or nutrients according to sensor observed needs (e.g., site-specific management). Other sensors collected information that can be used in the evaluation of production success (e.g., quality and amount of yield). The most advanced sensor systems were used for automated control or adjust of machines or vehicles (Thessler et al., 2011).

The spatial resolution of spaceborne sensors ranges nowadays from a kilometre to about half a meter, depending on the sensor. In general a distinction is being made in:

- *Low Resolution Optical Satellite Data*: 250m - some km spatial resolution by multi-spectral sensors like GEOS, Meteosat, NOAA, Vegetation and Modis.
- *Medium Resolution Optical Satellite Data*: 80m - 180m spatial resolution by multi-spectral sensors like Landsat MSS, RESURS-01 (MSU-SK) and IRS-1C (Wide Field Sensor - WiFS).
- *High Resolution Optical Satellite Data*: 5m - 30m spatial resolution by panchromatic or multi-spectral sensors or analogue camera systems such as Landsat TM, SPOT PAN and MS, IRS-1C/D (PAN and LISS), KFA 1000, MK4, etc.
- *Very High Resolution (VHR) Optical Satellite Data*: 1m - 4m spatial resolution by panchromatic or multi-spectral sensors, e.g. Worldview-2 and Quickbird with half a meter resolution for panchromatic band and 2 meter for the multi-spectral bands.

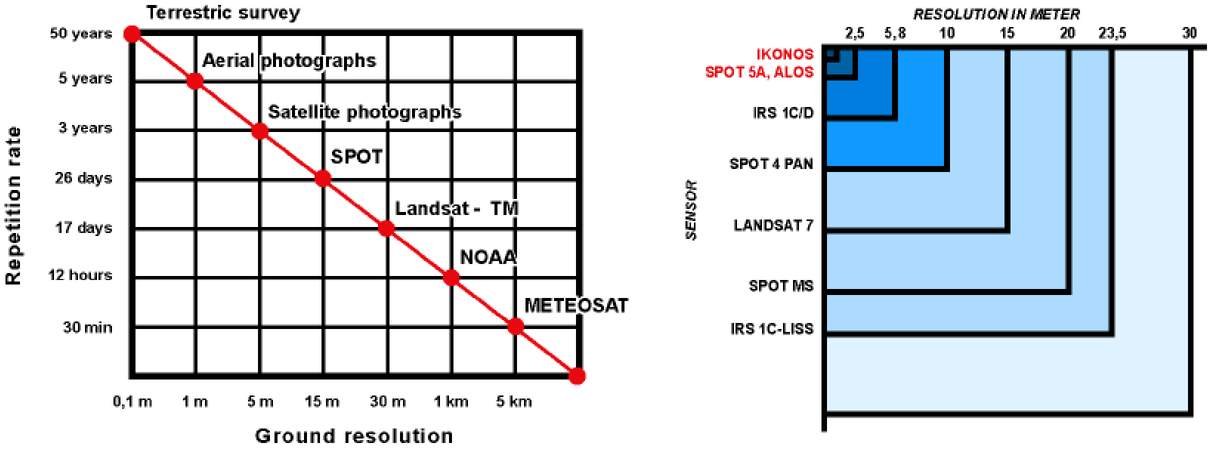

Figure 3 Spatial and temporal resolution of satellite sensors. Source: http://dib.joanneum.ac.at/edtr/satsys.html.

There is a clear trade-off between spatial and temporal resolution. The higher the temporal resolution the lower the spatial resolution. The European Space Agency (ESA) is developing five new missions called Sentinels specifically for the operational needs of the European GMES programme. The Sentinel missions are based on a constellation of two satellites to fulfil revisit and coverage requirements, providing robust datasets for GMES Services. The Sentinels will be launched from 2013. These missions carry a range of technologies, such as radar and multi-spectral imaging instruments for land, ocean and atmospheric monitoring. For example, Sentinel-2 will carry an optical payload with visible, near infrared and shortwave infrared sensors comprising 13 spectral bands: 4 bands at 10 m, 6 bands at 20 m and 3 bands at 60 m spatial resolution, with a swath width of 290 km. The mission orbits at a mean altitude of approximately 800 km and, with the pair of satellites in operation, has a revisit time of five days at the equator (under cloud-free conditions) and 2–3 days at mid-latitudes (source: http://www.esa.int/Our_Activities/Observing_the_Earth/GMES/Overview4). Sentinel -2 has the feasibility to calculate the red edge index for the detection of nitrogen deficiency.

An example of a typical spectrum for photosynthetic (green) vegetation is given in Figure 4 , but characteristic spectra relevant to land cover and habitat mapping are also available for non-photosynthetic (brown) vegetation, soils, water (in liquid and frozen form), bare areas and urban surfaces (Lucas et al., 2012, BIOSOS).

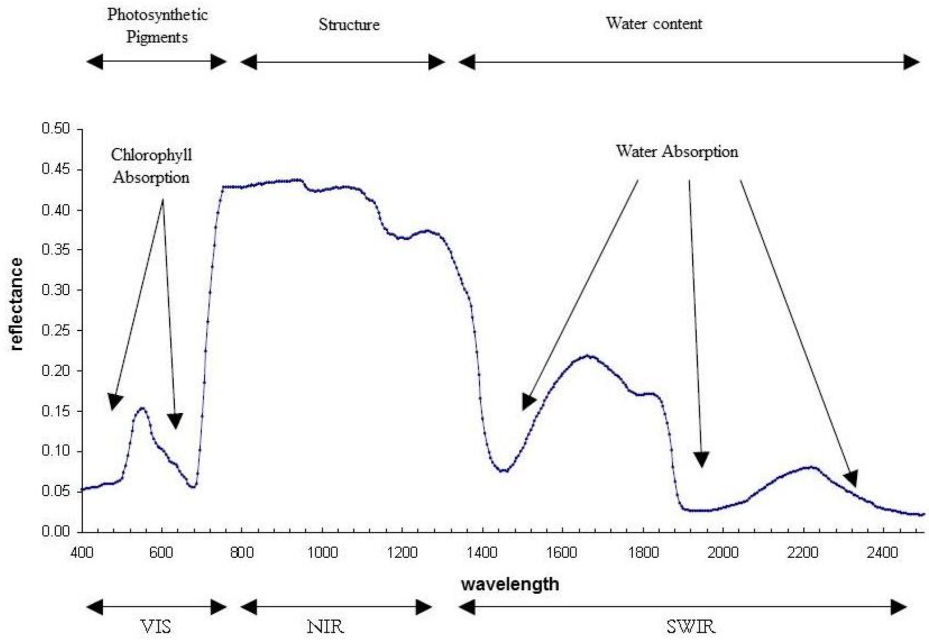

Figure 4 Typical spectra for vegetation highlighting the main contributors to reflectance

Within the vegetation (photosynthetic) spectra, characteristic features include the green peak, red edge and NIR plateau with absorption features (relating to moisture content) evident in the latter and also in the SWIR wavelength regions. Reflectance in the visible regions is primarily a function of pigment concentrations in foliage whilst in the NIR and SWIR, the internal leaf structure and moisture content of the leaves respectively influence reflectance (Swain & Davis 1978). In all cases, it should be noted that the reflectance of vegetation canopies varies from that of individual components (e.g., leaves, branches); largely because of the different contributions to the reflectance from plant materials and also the underlying surface and shadowing as a function of canopy heterogeneity, which particularly influences the NIR and SWIR wavelength regions.

The loss of pigments, cell structure and moisture content during senescence of leaves leads to the loss of most of the characteristic features of green leaves (with the exception of the water absorption features) and the transition to the spectral curve typical of non-photosynthetic vegetation. Dead wood exhibits similar spectra to that of dead leaves and, as these components ultimately develop into soil, the spectra of the latter often contain similar spectral features when derived from vegetation (e.g., humic soils). When soils are derived from rock weathering, their reflectance contains elements of the contained minerals, which are often distinct and thereby allow the generation of reference spectral libraries. The reflectance of water in the visible regions is typically < 10-15 % depending on, for example, sediment loads and the characteristics of the bed in shallow waters, but is lower (typically close to zero) in the NIR and SWIR regions and hence the more moisture contained within materials, the lower their reflectance. Shadow exhibits a very similar reflectance to water and hence is often confused spectrally but can also be used interchangeably in some cases (e.g., in spectral unmixing). When water is in a frozen state (i.e.. as snow or ice), the reflectance is considerably higher although then varies as a function of surface contaminants in the visible regions (e.g.. dust) or grain size, with lower NIR reflectances associated with larger grain sizes because of the associated reduction in the amount of air/water interfaces. Hence, the reflectance of snow in the visible and near infrared regions can indicate condition. In the shortwave infrared regions, snow and ice have very low reflectance allowing differentiation from cloud. Through knowledge of the reflectance characteristics of surfaces, an insight into the use of spectra for the description and discrimination of surfaces can be obtained and used to assist the classification process. A large number of studies have used spectral reflectance data to differentiate plant species and communities on the basis of differences in spectral reflectance, with this being attributed largely to differences in foliar chemistry, the internal structure of leaves, moisture content and the overall canopy structure (e.g., in terms of shadowing and relative amounts of plant components; leaves, branches). As examples, Lucas *et al.* (2008) extracted reflectance spectra (based on CASI data) from the sunlit portions of delineated tree crowns in Australia savannas, discriminating species of *Callitris*, *Eucalyptus*, *Acacia* and *Angophora* through discriminant analysis. Lu *et. al.* (2009) used hyper-spectral date to map the distribution of two spectrally similar grasses (*Miscanthus sacchariflorus* and *Phragmites australis)* in Japan on the basis of subtle differences in canopy density, leaf and canopy structure as well as biochemical properties. The benefits of using hyper-spectral data for mapping aquatic vegetation (e.g., different species of *Spartina* in San Francisco Bay, USA; Rosso *et al..* 2005), identifying and mapping invasive species(e.g.Ustin et al. 2004; Hestir et al. 2008; Walsh et al. 2008; He et al. 2011),; and differentiating between trees of the same species that are of different ages and sizes have also been conveyed (Christian & Krishnayya 2009).

In short remote sensing can contribute to:

1. Identify spatially the land cover class grassland and in some cases specific types of grasslands. There are many different local and regional grassland classification schemes (floristic, habitat, climatic, management, use etc.). In most cases floristic composition plays an important role and is not that easy to distinguish from satellite imagery.

2. Identify grassland parameters. These parameters include amongst others LAI, fraction cover, canopy shade, gap fraction soil, biomass content, soil moisture (indirectly), canopy coverage etc. The biophysical parameters that can be retreived from GMES data sources (e.g. GEOLAND-2) are amongst others:
    a) LAI and FAPAR are also classical parameters to quantify green vegetation (so we refer in fact to green LAI or GLAI). They are strongly correlated with fCover (but the relation between LAI and fCover is far from linear). It is a direct input into grass vegetation density product.
    b) fCover: fractional green vegetation cover (FVC) is a useful parameter for many environmental and climate-related applications. Comparing to previously used NDVI, it has several strong advantages: absolute parameter (sensor-independent), robustness to thin clouds, fully scalable at different spatial resolutions
    c) Canopy Shade Factor (CSF) : this parameter allows to characterize the amount level of shadows self-cast on the canopies, and so in many conditions to discriminate rough canopies (forests, shrub) from flat, homogeneous canopies (crops and grasslands)
    d) fSoil: quantifies the gap fraction of soil in the image, and relies on the capacity to discriminate a third contributor that is brown or non-photosynthetic (NPV) vegetation. It can be most useful to identify intensive agriculture practices with bare soil event.

emote sensing can play further a role in: grassland transpiration, grassland emissions and fluxes, grassland dynamics and phenology, grassland albedo, grassland productivity, chlorophyll and water content and vegetation condition and structure.

Because of this broad scope of remote sensing applications we narrowed a further literature review down to i) remote sensing and grassland productivity and ii) remote sensing and nitrogen.

Remote sensing and grassland productivity

Remote sensing offers a potential alternative to tedious hand sampling as a means of monitoring vegetation condition and estimating productivity over large areas of grasslands. Remote measurements of canopy spectral reflectance can provide a rapid and non-destructive method for assessing plant canopy biophysical parameters (i.e., green leaf area and biomass). Red and near infrared reflectance have been found to best correlate with amount and duration of green leaves (Tucker, 1977; Wiegand et al., 1979; Holben et al., 1980; Kimes et al., 1981; Hatfield et al., 1985). In general, these studies concluded that green leaf-area of plants can be estimated from measurements of red and near infrared spectral reflectance (Weiser et al., 1986). And, since green leaves are actively involved in evapotranspiration and photosynthesis, above-ground phytomass also can be estimated from remotely sensed data (Tucker and Miller, 1979; Boutton and Tieszen, 1983). A literature review based on the direct empirical relationships between canopy biophysical parameters and spectral reflectance demonstrated, however, a great degree of site and data-set dependence, and differences in relationships found before and after maximum growth (Hatfield et al., 1985). In an indirect approach, total above-ground phytomass was estimated from the fraction of absorbed daily PAR estimated from spectral reflectance measurements (Asrar et al., 1985b). The total above-ground phytomass values were computed as:

$$GP = \sum_{t=I}^{N} I_o K_f E_{PAR} K_m \qquad \text{(Eq. 1)}$$

where I_o is the daily solar energy (MJ M^{-2});
K_f is is the fraction of energy in the PAR region (assumed to be 0.5);
E_{PAR} is the fraction of absorbed PAR estimated from RO (Red ratio = NIR/RED) ;
K_m is the photochemical ranging from 1.4 to 3.4 g MJ^{-1}

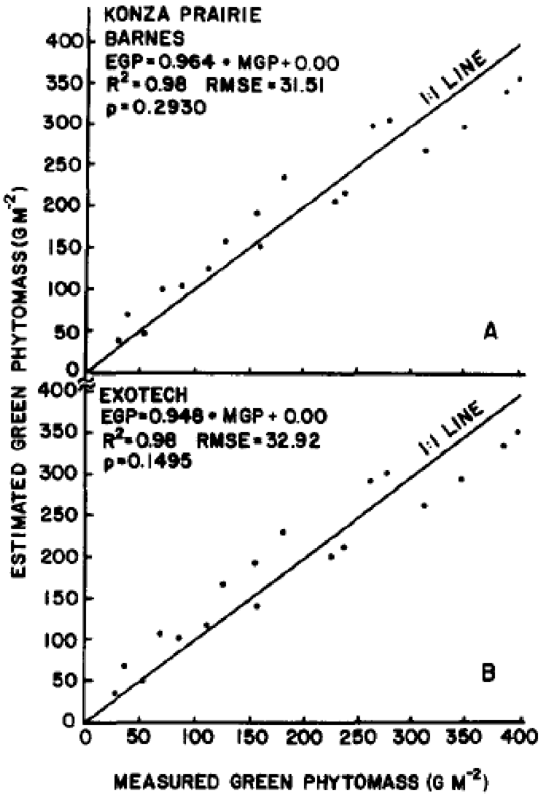

Figure 5 Estimated versus measured total green phyotomass for Banes (A) and Exotech (B) data (source: Weiser et al., 1986)

The direct relationships between spectral reflectance and LAI or phytomass were site-specific and differed for the two years of this study. The indirect approach for estimation of both LAI and phytomass was site- and year-independent, and provided more reliable estimates of these parameters (Weiser et al., 1986).
Another study (Bédard et al., 2006) used NDVI composites from NOAA AVHRR (at 1 km resolution) and TERRA MODIS (at 250 m resolution) to estimate natural pasture productivity in Alberta, Canada. The best result was obtained with biomass compared with mean MODIS NDVI, with a correlation coefficient of 0.74 (Biomass compared with mean AVHRR NDVI had a coefficient of 0.71).

The relationships between NDVI and pasture yields is a s follows:

$\text{biomass} = (8.957 \times 10^2) \times \text{Mean MODIS NDVI} - 2.854 \times 10^2$ (Eq. 2)

(correlation coefficient = 0.74)

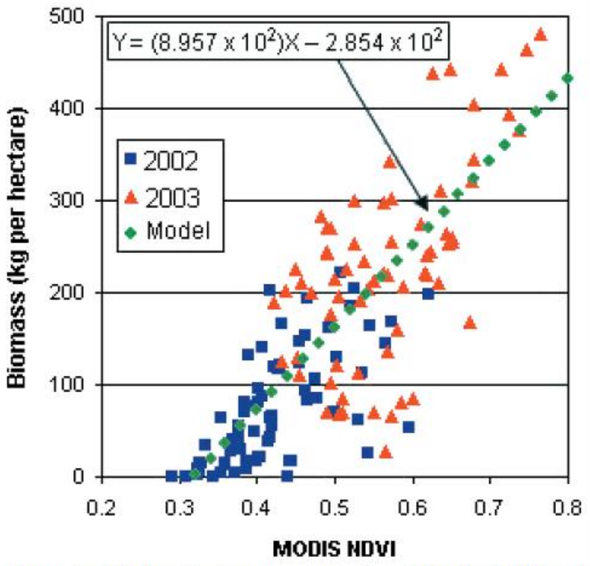

Figure 2. Relationship between mean Terra MODIS NDVI and pasture productivity between 9 May and 27 July for 2002 and 2003.

Figure 6 Relationship between mean Terra MODIS NVDI and pasture productivity between 9 May and 27 July for 2002 and 2003 (Bédard et al., 2006).

The authors (Bédard et al., 2006) realize that pasture productivity expressed as a density of dry biomass will not necessarily perfectly fluctuate with changes in the NDVI. The relationship might change with different types of grassland.

Freely accessible and downloadable are the MODIS primary production products (MOD17), which are the first regular, near-real-time data sets for repeated monitoring of vegetation primary production (GPP and NPP) on vegetated land at 1-km resolution at an 8-day interval. Public should be aware that the performance of the algorithm can be largely influenced by the uncertainties from upstream inputs, such as land cover, FPAR/LAI, the meteorological data, and algorithm itself (Zhao et al., 2004).

2.2.4 Operational remote sensing systems for yield monitoring

Research on improving the simulation of crop canopy development has mostly focused on the use of sequences of high spatial resolution satellite imagery (20-30 m) to either recalibrate crop model parameters such as the emergence date, or to integrate the observations in a model using a forcing or updating approach (De Wit, A., 2007, Bach and Mauser, 2003; Boegh et al., 2004; Bouman, 1995; Guérif and Duke, 2000; Maas, 1988; Moulin et al., 1998; Prevot et al., 2003; Schneider, 2003). Although results demonstrated that many crop model states (e.g. simulated biomass, leaf area index, yield) could be improved using satellite observations, such methods have proven difficult to be applied in crop yield forecasting applications operating at regional to continental scales. The main reason for this slow adoption is the disparity in scales between the process (crop growth on fields often as small as 1 hectare) and the type of observing system that can be used operationally and economically over large areas with high temporal frequency (satellite sensor observations with a spatial resolution ranging from 250 m to 1 km). Given the relatively coarse spatial resolution of such satellite sensors, in many parts of the world the instantaneous field of view (IFOV) covers a mixture of various land cover types, making if difficult to estimate the value of crop states (assessed through LAI or biomass) for specific crops. Some studies attempted to cope with the subpixel heterogeneity directly (DeWit, 1999; Fischer, 1994; Moulin et al., 1995), while others attempted to unmix a coarse resolution signal into its underlying spectral components (Cherchali et al., 2000; Faivre and Fischer, 1997). The general drawback of

these approaches is that they rely on the availability of ancillary data (e.g. land cover/crop maps) which are usually not available over large areas for the current growing season. A few studies describe yield forecasting results obtained by integrating coarse resolution satellite observations in crop simulation models at regional scales over areas with relatively homogeneous land cover. For example, Doraiswamy et al. (2005) used Leaf Area Index derived from MODIS 250m observations over Iowa (U.S.) to recalibrate crop model parameters, while Mo et al.(2005) used Leaf Area Index derived from NOAA-AVHRR as a forcing variable in a crop model for the North China Plain. Their results demonstrate that crop yield estimates improve when satellite observations are used to update or force a crop model. Nevertheless, these techniques can only be applied over regions with homogeneous land cover and a limited number of crop types (De Wit, A., 2007).
Especially the launch of the European SENTINEL satellites with a maximum spatial resolution of a 10 meter for SENTINEL-2 and a revisit time of a few days in combination with radar satellite SENTINEL-1 (that is not hampered by cloud cover) can provide a new boost for the integration of satellite imagery with crop yield models to assess actual yields.

CGMS and MARS-OP3

For the implementation of the Common Agricultural Policy, the European Commission needs timely information on the agricultural production to be expected in the current season. This is a main concern of the MARS-project (Monitoring Agricultural Resources) of the AGRI4CAST and FOODSEC Actions of the Directorate General Joint Research Center (JRC) of the European Commission in Ispra (Italy).

In 1988 the Council of Ministers of the European Union (EU) decided already to set up a project to improve the provision of agricultural statistics which are necessary to manage the large budgets involved in the European Common Agricultural Policy (CAP). This project has become known as the MARS project (Monitoring Agriculture by Remote Sensing) and it comprised different activities such as regional crop inventories, satellite-based rapid crop area estimates, assessment of foreign agricultural production and an agricultural information system (Council of the European Community, 1988).
The agricultural information system activity focused on providing early crop yield forecasts for the EU countries and used two approaches for providing indicators for crop yield prediction. The first approach used indicators derived from low resolution (1-km) sensors such as NOAA's AVHRR sensor (Advanced Very High Resolution Radiometer) onboard POES (Polar Operational Environmental Satellite). Daily AVHRR imagery were recorded, stored and processed into 10-day composites (De Wit, A., 2007). Crop growth indicators such as surfacetemperature or Normalised Difference Vegetation Index (NDVI) where derived that could help in characterizing the growing season and quantifying the crop yield (Sharman, 1992). The second approach focused on developing an agrometeorologic system employing crop growth models to estimate crop yield. For this purpose, weather data from weather stations were interpolated to a 50 × 50 km grid and the WOFOST crop growth model (WOrld FOod STudies) was applied to each grid. The simulation results per crop type were stored in a database and spatially aggregated to administrative regions in order to be used as predictors for crop yield forecasting. This system has become known as the Crop Growth Monitoring System (CGMS) (Diepen, 1992; Vossen and Rijks, 1995; Genovese, 1998).
Despite the initial focus on the use of remote sensing techniques for crop yield forecasting within the MARS project, it was gradually recognized that remote sensing derived indicators played a minor role in forecasting of crop yield in Europe, as Vossen and Rijks (1995, page 5) state: "Although remote sensing techniques are presently being turned into operational tools for crop acreage inventories, land utilisation assessment and low resolution vegetation condition monitoring, they do not permit yet, for various reasons, the quantitative prediction and assessment of regional or national mean crop yields within the E.U." Vossen and Rijks (1995, pages 5 & 108) also mention several reasons for the relatively poor performance of using optical, low resolution satellite data for crop yield forecasting in Europe (De Wit, A., 2007):

1. Land cover in Europe is highly fragmented and interpretation of low resolution data is therefore often ambiguous because it represents most often a mixture of several land cover types;

2. Lack of consistent time-series of remote sensing data due persistent cloud cover, sensor calibration problems or satellite mission continuity.
3. This renders regression analyses on time-series of remote sensing derived indicators for yield forecasting problematic;
4. The non-availability of proven models to relate satellite information to quantitative yield estimates on a regional scale. This is related to the lack of sensitivity of commonly used remote sensing indicators (e.g. NDVI) in much of Europe due to the high crop production levels and the relatively small year-to-year variability.

Except for a lack of sensitivity for some regions and crop types, the agrometeorologic approach employed within CGMS does not suffer from the above-mentioned drawbacks: The interpretation of results is straightforward because specific crops can be modelled and the results can be easily compared with statistical data. Moreover, the results are available and consistent over long time-series due to a long-term record of meteorological observations available. As a result, the approach for quantitative crop yield prediction within the MARS project gradually shifted towards an agrometeorologic approach, while remote sensing derived indicators were merely used as qualitative descriptors of the growing season. Operational aspects of the system have been gradually improved and integrated into an automated processing chain covering the full cycle from ingestion of weather to the forecasting of crop yield and the automated production of maps, charts and tables (De Wit, A., 2007).

The main goal of the MARSOP3-project (www.marsop.info), implemented by Alterra (NL) in co-operation with VITO (BE),University of Reading (UK), GISAT (CZ)and Meteo Group (NL), is to monitor weather and crop conditions during the current growing season and to estimate final crop yields for Europe and other continents by harvest time – for the European Commission. To facilitate the monitoring and estimation, tools ranging from remote sensing techniques to agro-meteorological models (CGMS, FAO-WSI) are applied. Immediate users of the projections are the European Directorate General for Agriculture and Rural Development and the EuropeAid Office. The MARS project also has links with the Food and Agriculture Organization of the United Nations (FAO) and national research organisations, such as in China. Service contract of MARS-OP3 is for the period 2008-2013 (predecessors were MARS-OP1 en MARS-OP3).

Remote-sensing applications (Low resolution satellite) data feed into the system and contributes to some improvements in the agricultural forecasting models as well as to regionally-based models. Information from meteorological satellites is used in addition to the data delivered by meteorological stations (e.g. radiation measured by satellites at the resolution level of 5 km). The remote-sensing information is processed to produce “measured” vegetation indicators, which can be compared with the agrometeorological indicators and used for the statistical analysis. Low to medium resolution satellite sensors are utilised: SPOT Vegetation/NOAA-AVHRR (about 1 km resolution) and MODIS (about 300-500 m resolution).

In cases, outside Europe, where less agro-meteorological data is available, and the actual yields differ much from year to year, the role of remote sensing becomes larger. Nevertheless, small agricultural fields, often with multiple crops remain a big challenge to assess, even with the launch of the SENTINEL satellites.

Canadian Crop Condition Assessment Program (CCAP)2

CCAP (www.statcan.gc.ca) provides weekly cropland and pasture condition reports across Canada and the northern United States, in near real-time based on analysis of low resolution satellite data. Historical conditions are also available at various levels of geography. The Agriculture Division of Statistics Canada has the mandate to collect census and survey information regarding all forms of agriculture in Canada, and provide it in an

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[2] Directly derived from http://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&SDDS=5177&Item_Id=74968&lang=en#a2

expeditious manner to clients, often government policy makers. Long ago Statistics Canada realized that new technologies such as satellite remote sensing and geographic information systems (GIS) could reduce costs and provide valuable information in support of its operations, without imposing additional response burden on producers. The Crop Condition Assessment Program (CCAP), developed and maintained by the Remote Sensing and Geospatial Analysis Section (RSGA) within the Agriculture Division, is a prime example of such an application. The CCAP combines remote sensing, GIS, and the Internet to provide reliable, objective, and timely information on crop and pasture/rangeland conditions using a mapping application for the whole Canadian agricultural area and the northern portion of the United States. The National Oceanic and Atmospheric Administration (NOAA) series of satellites carrying the Advanced Very High Resolution Radiometer (AVHRR) records images of the entire Earth's surface twice a day at one kilometre resolution. This detector captures two spectral bands (red and infrared) that have proven to be extremely useful for vegetation monitoring to produce the Normalized Difference Vegetation Index (NDVI). Throughout the growing season from early April to mid October, on a weekly basis, Statistics Canada receives a 7-day composite of AVHRR images. Once the composites are received at Statistics Canada, some additional value-added processing is completed before the pplication is updated on the internet, normally on the same day that the data is received. This makes the CCAP an efficient tool to quickly and objectively depict agriculture conditions in near real time. Federal and provincial government agencies, grain marketing agencies, crop insurance companies, researchers and producers are typical users of the CCAP.

New for 2010, the CCAP has been further enhanced with the integration of the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data. At a spatial resolution of 250 metres and using its red and near infrared spectral bands, the MODIS sensor is able to show vegetation conditions (NDVI) with a higher spatial resolution and accuracy than the AVHRR imagery. RSGA has built an interactive mapping interface that allows users to view, via the Web, value-added satellite images and map products as well as charts and tabular data. Image products show vegetation conditions on a pixel by pixel basis while map products illustrate the predominant vegetation condition by regions as large as Census Agricultural Region, or as small as municipalities or townships. Current or historical conditions using the AVHRR-based application can be compared to the 23-year normal (10 years for the MODIS data) or to any other period of the available database. Severe droughts, increasing competition among exporters, and the instability of crop products markets have underscored the importance of having accurate and timely information on crop conditions and potential yield. CCAP is able to supply the user community with frequent updates over a large geographic area well in advance of Statistics Canada's results of traditional surveys on crops.

USDA Crop Explorer

USDA Crop Explorer is a web mapping tool from USDA to enhance crop condition information (http://www.pecad.fas.usda.gov/cropexplorer/). The amount and variety of information that can be extracted from NASA satellite data form a rich resource that is largely untapped by the applications user community. To rapidly bridge the gap between NASA information systems and services and the practical needs of the applications (and research) community, the Goddard Earth Sciences Data and Information Services Center (GES DISC) has collaborated with the Florida International University High Performance Database Research Center (FIU HPDRC) and the U.S. Department of Agriculture Foreign Agricultural Service (USDA FAS) to demonstrate the feasibility of making NASA data more easily and seamlessly accessible via the Web, from within the FIU's TerraFly and the FAS' Crop Explorer environments, respectively. TerraFly currently serves a broad segment of the research and applications community (some 10,000 unique users per day), by facilitating the access to various textual, remotely sensed, and vector data. Crop Explorer is the primary decision support tool used by the FAS analysts to monitor the production, supply, and demand of agricultural commodities worldwide. The key NASA information system providing the data integrated into TerraFly and Crop Explorer is the GES DISC Interactive Online Visualization and Analysis Infrastructure (Giovanni), which enables users to easily and quickly obtain science information from the data, without having to download and handle large amounts of data. The seamless integration was effected by deep linking both TerraFly and Crop

Explorer with Giovanni, to provide a dynamic, context-sensitive Web service for rainfall data. Planned work includes adding other measurements (e.g., aerosol, ozone, ocean color, sea surface temperature) and converting both deep linked systems to be compatible with OGC and OPeNDAP data interoperability standards. The integrated systems should notably contribute towards progress along several NASA Applications of National Priority, such as Agricultural Efficiency, Disaster Management, Ecological Forecasting, Homeland Security, and Public Health.

China's Crop Watch

The past 40 years have seen commendable progress in the use of remote sensing to monitor crops. Since the 1970sremote sensing has made it possible to obtain quantitative crop-specific information on a regional scale：the China CropWatch System(CCWS) has been a success story. With about 20 years research experience behind it, the Institute of Remote Sensing Application(IRSA) of the Chinese Academy of Sciences(CAS) developed the system in 1998 and has operated it ever since. CCWS covers entire China and 46 major grain—growing countries of the world. The System monitors the condition of the growing crop, crop production, drought, crop plantation structure, and cropping index. After 10 years' operation and improvement, CCWS began publishing, and currently publishes 7 monthly bulletins and 20 newsletters every year。Which have become important sources of information for government bodies including the State Council, Ministry of Agriculture Ministry of Commerce, State Grain Administration, and State Statistics Administration. CCWS consists of seven components, Which are as follows：crop growth monitoring, drought monitoring, grain production estimation, crop production predicting, crop planting structure inventory, cropping index monitoring, and grain supply-demand balance and early-warning. The monitoring can be carried out on different Scales or levels ranging from a village and a county through a province and the whole country to the main producing countries in the world and the entire globe.
The accuracy of each monitored item in the entire content of CCWS is greater than 95％and the relative error between years is less than 1%, Which meets the users' requirements and expectations. CCWS system and information service can be customized for all kinds of users, whatever their need for crop-specific information may be (www.cropwatch.com.cn).

Australia's Pastures from Space

The Pastures from Space program provides estimates of pasture production during the growing season by means of remote sensing. Satellite data is used to accurately and quantitatively estimate Pasture Biomass or Feed On Offer (FOO) or combined with climate and soil data is used to produce Pasture Growth Rate (PGR) estimates. Estimation of PGR and FOO using remote sensing provides temporal and spatial information on feed resources allowing producers to more effectively manage their enterprise and potentially raise the productivity and profitability of their businesses. It is also possible that an objective measure of the spatial variation of pasture production will highlight opportunities to improve the environmental management of the landscape. Matched with electronic delivery of the information (email or web based) near real time decisions can be made. The technology has been widely trialed by Western Australian farmers, where PGR information is broadcast on ABC Radio and signposted in regional areas. PGR estimates for Shires in the Southern agricultural or Mediterranean regions of Australia are now being developed and trialed nationally. This information and subscription is available through Fairport Technologies (http://www.pasturesfromspace.csiro.au/).

2.2.4 Modeling

There is a wide variety in modeling approaches of grassland production. In this study we distinguish mechanical process based models and empirical models. As a special case of empirical models we consider the feed balance approach.

Mechanistic models

Many models for predicting grassland production have been developed in recent years. They are often based on growth, senescence, litter and standing biomass, using data on incoming radiation, temperature, soil moisture, day length and altitude. Taubert et al. (2011) evaluated 13 grassland models which varied broadly in their objectives, structure and complexity. The objectives range from detailed reproduction of the architecture of plants to the analysis of below-ground resource use or impacts of climate change or management on grasslands. The structural design of the models including their time steps, main variables, abiotic factors, considered competition processes and management activities are listed in Table 5 and Table 6. The Hurley Pasture Model comprises a dynamic, mechanistic ecosystem model with a great deal of complexity (Thornley and Verberne, 1989; Thornley and Cannell, 1997; Thornley, 1998, 2001). The process-based model structure simulates daily fluxes of carbon, nitrogen and soil water by coupling soil, plant and grazing submodels. Central variables of, e.g. the plant submodel, comprise structural dry matter, carbon and nitrogen substrate, and leaf area, additionally structured by age and plant components. As a result, the plant submodel already covers 21 state variables and 60 parameters inducing a high degree of complexity, which may cause difficulties in the parameterization of species-rich sites (Thornley and Cannell, 1997). Therefore, in simulation studies of the Hurley Pasture Model only a generic C3 grass species was assumed (Thornley and Cannell, 1997; Thornley, 1998). The daily working PaSim model is based to a large extent on the Hurley Pasture Model, but it also includes certain processes such as leaf stomatal resistance or the dynamic change of a plant's fractional nitrogen content in greater detail (Riedo et al., 1998, 2000). Additionally, some new aspects, e.g. the reproductive developmental stage and the non-linear temperature dependence of the shoot and root growth rates, were introduced. As in the Hurley Pasture Model, a plant's state is described by the structural dry matter of the plants in different compartments (e.g. leaves, stem, sheaths) as well as the nitrogen content. Due to the high degree of complexity, as in the Hurley Pasture Model, simulation studies assumed only a single species representing a kind of a mean species for the entire community. In a less complex way, the process-based GraS-Model simulates daily species-specific vegetation cover dynamics (Siehoff et al., 2011). Different single species as well as various plant groups (e.g. tufted plants or erect forbs) are simulated on the population-level by coupling a simple plant competition model and a land use model, each of them raster-based. Utilization indicator values for trampling, cutting and grazing allow the incorporation of management activities. However, in this model species compete only for space, but the influence of different abiotic factors as well as competition between species for e.g. soil water would lend further insight.

In contrast, the grassland model developed by Schippers and Kropff (2001) does include such abiotic factors as radiation and temperature. This daily working model also shows a less complex model structure including dry mass of the plants in different compartments (flower, shoot, root, and reserves) and nitrogen content as state variables. This lower level of complexity allows the simulation of several single species competing with each other. Competition processes are considered to take place above-ground for light and below-ground for nitrogen. An extended spatially explicit model version enables an individual-oriented modelling concept based on the self-thinning law (Yoda et al., 1963). Overall, this model provides a potential tool for simulating species-rich herbaceous communities. The model of Schippers and Kropff (2001) does not consider water stress and competition for water between individuals, which would also be of great interest. The LINGRA grassland model, on the other hand, includes water stress by using a water shortage factor, which influences light-use efficiency (Schapendonk et al., 1998). The calculation of light-use efficiency is part of the source-sink concept of the model. Within this scope, light-use efficiency is used for simulating the daily source carbon flow, while temperature-driven leaf area and tiller dynamics are used for modeling the daily sink carbon flow. Interactions between both fluxes are integrated via the plant's storage pool. Simulation studies were carried out for single species populations throughout Europe. The model shows some important characteristics needed for simulating LIHD and HILD grasslands. Tiller and leaf area dynamics are modeled dependent on radiation intensity, temperature, soil water content and defoliation. Although water stress is considered, the inclusion of nitrogen stress as well as inter-specific competition for water and nitrogen between individual tillers would increase the informative value of the model.

Also based on the light-use efficiency concept, the model of Duru et al. (2009) follows a contrary strategy. They focus mainly on the daily accumulation of above-ground herbage mass by taking into account the temperature-driven growth of green leaf area and the reduction of leaf area due to senescence. Factors considering water and nutrient stress are integrated by limiting the growth of herbage mass. Simulations showed herbage growth accumulation of a community consisting of three plant functional groups, but do not include an individual's tiller dynamic and resource use. However, this would be interesting for a detailed view of intra- and inter-specific competition processes between individual tillers, especially for water and nitrogen.

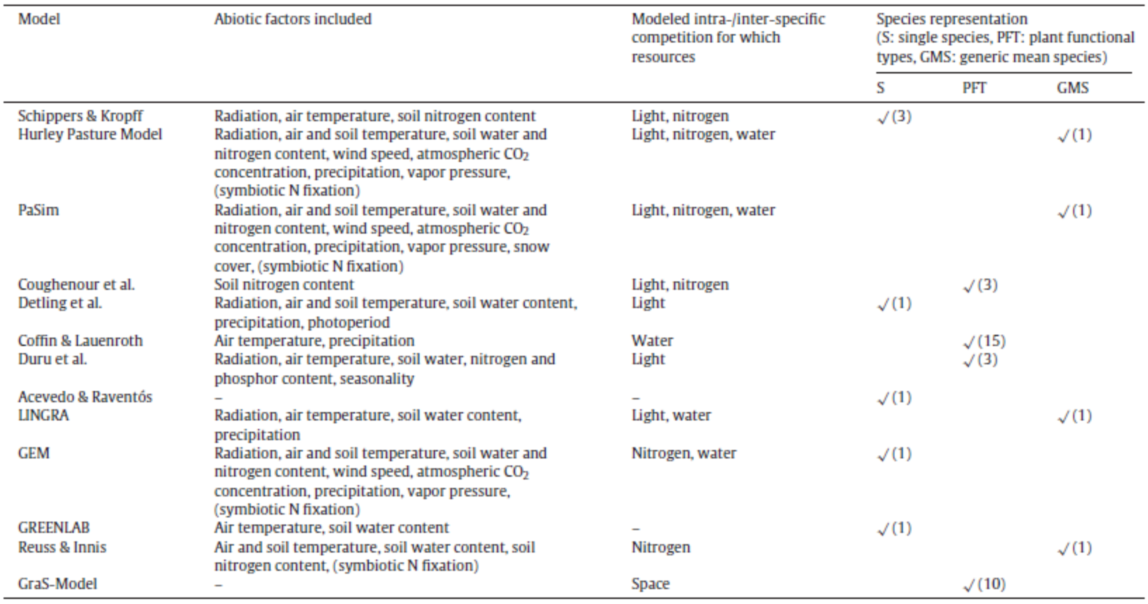
The model developed by Coughenour et al. (1984) considers senescence and maturation. It simulates the daily primary production of biomass of perennial grasses. For modeling processes like photosynthesis or senescence potential rates are modified with reduction factors. Additionally, a shoot submodel including different stages of aging allows the simulation of tiller dynamics per plant. Simulations were carried out using three different height groups (plant functional types) of tufted perennial grass species. Species that differ in growth form and characteristics are currently not included in this model. However, this would be useful for simulating European species-rich grasslands. Semi-arid models like the individual-oriented model of Coffin and Lauenroth (1990) focus mainly on competition for water resources between individual plants and a resulting water stress affecting the number of individuals per plant functional group. It uses the gap approach usually applied in forest models and focuses on below-ground resource use of 5 resource groups, which again were divided into 15 plant functional/species groups for simulation. Dynamics are simulated annually by the resource space proportionally assigned to the individual plants in the community and the below-ground gaps in the resource space produced by dying individual plants. As it is a semi-arid grassland model, the resource space is mainly determined by the soil water content or precipitation. However, for temperate regions competition for nitrogen and light and the resulting effects on the individual's growth and survival are as important as competition for water resources.

Detling et al. (1979) incorporate in their model structure the intra-seasonal impact of temperature, moisture, light and nitrogen on the biomass dynamics of the species Bouteloua gracilis. The daily simulated processes covered in the model comprise among others spring regrowth and the translocation of carbohydrates between leaves, crowns and roots. These are important aspects for temperate regions. The model is tested for one species only. But the consideration of detailed inter-specific competition for e.g. water, light, nitrogen and space would be revealing. The GEM model (Hunt et al., 1991) presents a producerdecomposer model comprising (1) the impact of abiotic factors on the primary production submodel and (2) feedbacks of the nitrogen flux. The model includes a water submodel, a plant submodel, a decomposer submodel as well as a fauna submodel and is designed for investigating climate change impacts on the daily carbon and nitrogen dynamics. Simulation studies were only carried out using a dominant single species and do not examine the inter-specific competition processes of species-rich communities.

Table 5 Overview of the reviewed models concerning time step, model structure, main variables and management activities considered (Taubert et al., 2012).

Model	Time step	Individual- (I) or population- (P) based calculations	Spatially explicit	Main variables	Management activities considered
Schippers & Kropff	Daily	P	✓	Above- and below-ground biomass and nitrogen content	Cutting, fertilization
Hurley Pasture Model	Minutes (variable)	P	×	Above- and below-ground biomass and nitrogen content, leaf area	Cutting, fertilization, grazing
PaSim	Minutes (variable)	P	×	Above- and below-ground biomass and nitrogen content, leaf area	Cutting, fertilization, grazing
Coughenour et al.	2 days	P	×	Above- and below-ground biomass	–
Detling et al.	Daily	P	×	Above- and below-ground biomass	Fertilization, irrigation
Coffin & Lauenroth	Annual	I	×	Number of individuals, above-ground biomass	–
Duru et al.	Daily	P	×	Leaf area index, above-ground biomass	Cutting
Acevedo & Raventós	0.1 months	I	✓	Above-ground shoot or leaf length	–
LINGRA	Daily	P	×	Above- and below-ground biomass, tiller number, leaf area index	Cutting, irrigation
GEM	Days (variable)	P	×	Above- and below-ground biomass and nitrogen	–
GREENLAB	Days to years (variable)	I	✓	Above-ground biomass, physiological age	–
Reuss & Innis	Daily	P	×	Above- and below-ground nitrogen, biomass	Fertilization
GraS-Model	Daily	P	✓	Above-ground occupied area/cover	Cutting, grazing and trampling

Table 6 Overview of abiotic factors considered in the reviewed models, the resources species compete for and the number and type of species represented (single species (S) e.g. Lolium perenne, plant functional types (PFT) e.g. grasses or legumes, or a generic mean species (GMS) for an entire community). For each model the number of simulated species or PFT is given in brackets (Taubert et al., 2012).



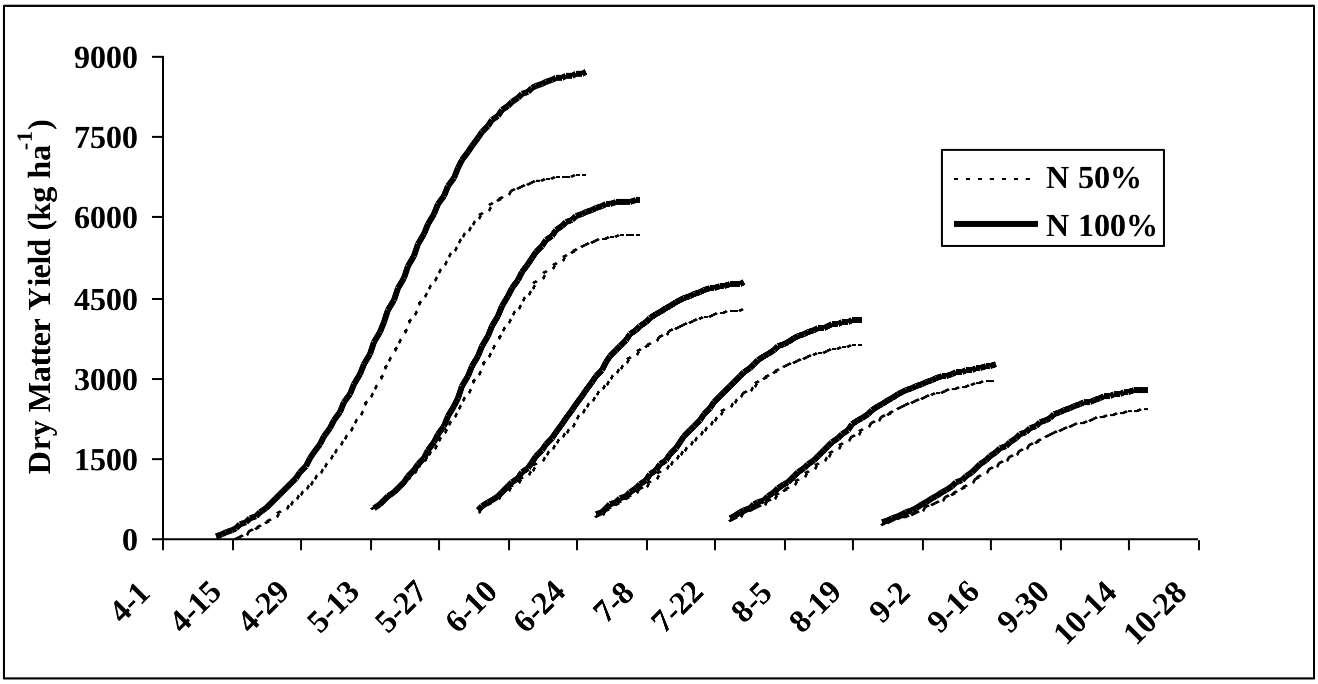
Model	Abiotic factors included	Modeled intra-/inter-specific competition for which resources	Species representation (S: single species, PFT: plant functional types, GMS: generic mean species)		
			S	PFT	GMS
Schippers & Kropff	Radiation, air temperature, soil nitrogen content	Light, nitrogen	✓(3)		
Hurley Pasture Model	Radiation, air and soil temperature, soil water and nitrogen content, wind speed, atmospheric CO_2 concentration, precipitation, vapor pressure, (symbiotic N fixation)	Light, nitrogen, water			✓(1)
PaSim	Radiation, air and soil temperature, soil water and nitrogen content, wind speed, atmospheric CO_2 concentration, precipitation, vapor pressure, snow cover, (symbiotic N fixation)	Light, nitrogen, water			✓(1)
Coughenour et al.	Soil nitrogen content	Light, nitrogen		✓(3)	
Detling et al.	Radiation, air and soil temperature, soil water content, precipitation, photoperiod	Light	✓(1)		
Coffin & Lauenroth	Air temperature, precipitation	Water		✓(15)	
Duru et al.	Radiation, air temperature, soil water, nitrogen and phosphor content, seasonality	Light		✓(3)	
Acevedo & Raventós	–	–	✓(1)		
LINGRA	Radiation, air temperature, soil water content, precipitation	Light, water			✓(1)
GEM	Radiation, air and soil temperature, soil water and nitrogen content, wind speed, atmospheric CO_2 concentration, precipitation, vapor pressure, (symbiotic N fixation)	Nitrogen, water	✓(1)		
GREENLAB	Air temperature, soil water content	–	✓(1)		
Reuss & Innis	Air and soil temperature, soil water content, soil nitrogen content, (symbiotic N fixation)	Nitrogen			✓(1)
GraS-Model	–	Space		✓(10)	

Empirical models

The farm model DairyWise (Schils et al., 2007) includes two separate models for the main forage crops grass and corn. The GrassGrowth model predicts the daily rate of DM accumulation of grass, including several feed quality parameters. It is an empirical model based on a series of field experiments on the main Dutch soils sand, clay and peat (Vellinga et al., 2004, Vellinga, 2006). All experiments comprised a range of N applications, from 0 to 600 kg/ha per year. Additional core experiments included a range of growth times for each growing cycle necessary to derive growth curves. Regression analysis was used to derive growth curves for the potential DM yield without water limitation. The actual, water-limited, DM yield was calculated with a drought factor which was related to soil type and groundwater level. Soils with lower ground water levels can have DM yield reductions up to 23% compared to soils with optimal moisture supply. All yields were based on perennial ryegrass (*Lolium perenne* L.) dominated swards.

The potential DM yield is a Gompertz function in which the maximum daily growth and the upper yield limit are the main traits. Both parameters are functions of a N supply factor comprising the effects of applied N, soil N, and residual N from previous fertilizer or manure applications. Different functions apply for the first and later growth cycles. An example of growth curves for individual growth cycles on sandy soil is shown in Figure 7. The N yield of grassland is the product of DM yield and N concentration, but it is affected by a N dilution factor, representing the effect of growing period on N concentration. The N concentration in grass is related to a N supply factor, comparable to the N supply factor used for DM yield. In the original experiments, harvested grass was analyzed for DM, crude fiber (CF), CP and crude ash (CA), enabling the calculation of OM digestibility (OMD), NE_L (VEM; 1 VEM = 6.9 kJ NE_L), digestible true protein and degraded protein balance (Tamminga et al., 1994). These calculation procedures were included in the feeding value sections of the model.

Figure 7 Growth curves for grassland without white clover on sandy soil in relation to N application and starting date. The N application level of 100% is equal to 120, 90, 60, 60, 30 and 30 kg/ha for the first to sixth growth cycle, respectively.



The annual yield of grassland is the sum of the yields per cutting (Table 7). As the yield in a certain cut is determined by its use, the annual yield of grassland is not a fixed value, but depended on the cutting and grazing management. If grass is grazed, the DM yield generally ranges between 1,000 and 2,000 kg/ha, and if it is cut for silage, the yield generally varies between 2,500 and 4,500 kg/ha. Therefore, annual yields are generally higher if the proportion of grass cut for silage increases. Common grassland use in the Netherlands consists of grazing with the inclusion of 1 to 3 silage cuts per year. Yet, there is an increasing trend towards cutting only, with higher yields but lower quality. With equal amounts of applied fertilizer, the DM yield increases among soil types in the order from sand, clay to peat. Nevertheless, peat soils usually receive less fertilizer N as the soil N supply is higher than on mineral soils (Hassink, 1995).

Table 7 Typical annual DM yields, nitrogen content and OM digestibility (OMD) of grass predicted by the model for different soil types, N application rates, and grassland management.

	Soil type	N applied (kg/ha)	Management	DM Yield (1000 kg/ha)	N content (g kg/DM)	OMD (%)
Grassland	Sand	200	grazing and cutting	12.3	28	80
	Sand	300	grazing and cutting	13.4	32	80
	Sand	300	cutting only	14.5	30	80
	Clay	300	cutting only	14.9	30	79
	Peat	300	cutting only	15.5	32	78

Bachinger and Reining (2009) developed an empirical statistical model for predicting the yield of from legume-grass swards within organic crop rotations based on cumulative water balances. The model was developed based on weather and soil data commonly available at field and regional scales. The main underlying hypothesis was that water use, calculated from cumulative water balances, can be used as a predictor of DM yield. The model was calibrated with data from a multi-year field experiment in Müncheberg, north-east Germany and was tested with data from other countries of Europe. In the calibration data set, highly significant linear relationships were found between water use and DM yield for DM yield of single harvests and for annual DM yield. The only additional variable significantly improving the prediction of DM yield was cut number. For the validation data set the DM yield for single cuts and annual yields was predicted with a similar accuracy as found with other models requiring the use of more information. The models described offer a straightforward weather- and site-specific means of predicting DM yield with a satisfactory level of precision, especially for annual DM yields (), and thus can help to reduce planning failures concerning forage and N supply in organic farming systems in Europe.

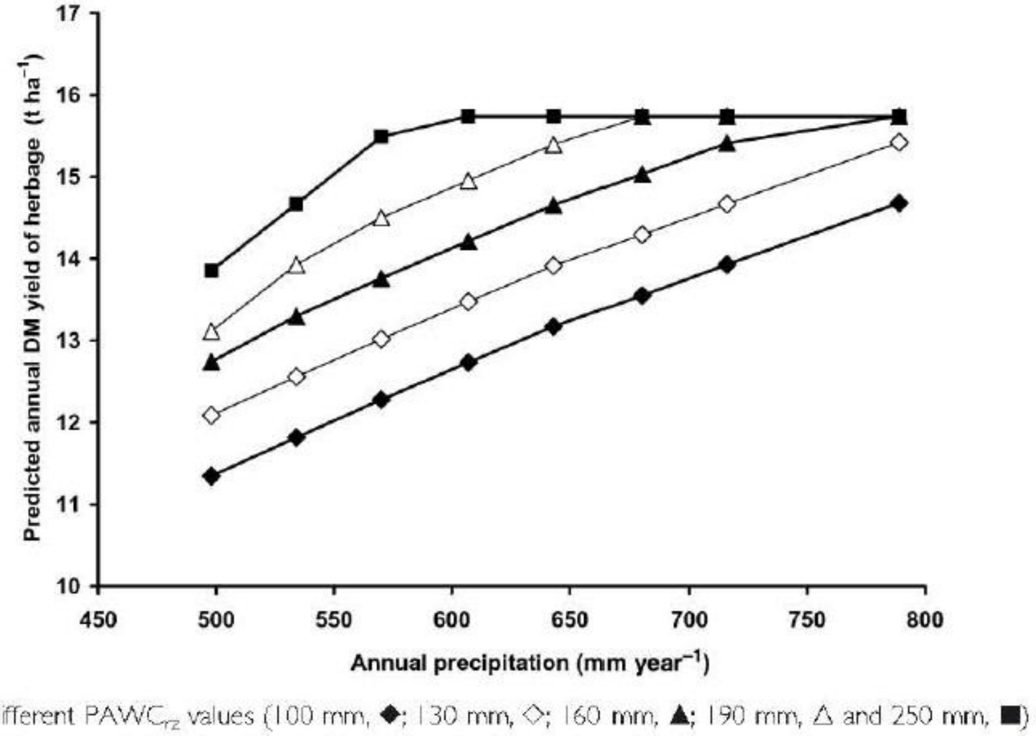


Figure 8 Effect of different PAWC (plant available water in root zone) values on dry matter yields predicted for different levels of precipitation (Bachinger and Reining, 2009).

Protin et al. (2011) estimated grassland productivity by using climate parameters in the French Piedmonts Pyrenean Mountains. The statistical models use linear regression linked yield with different prediction parameters. The model of first production cycle, without fertilization, links yield to sums of temperature accumulated from February 1st (Figure 9). The studied grasslands have very different production potentials without fertilization, so other parameters are tested to improve predictions. The index of nitrogen nutrition (INN) is the most pertinent variable. Two models are constructed according to grasslands INN: low or high. Nitrogen fertilization increases the growth rate if the nutrition status of grassland is not optimum (low INN) but has no effect otherwise. These models are included in a computer tool to improve predictions of grass yields and optimize the grassland management in the French 'Piedmonts' Pyrenean Mountain.

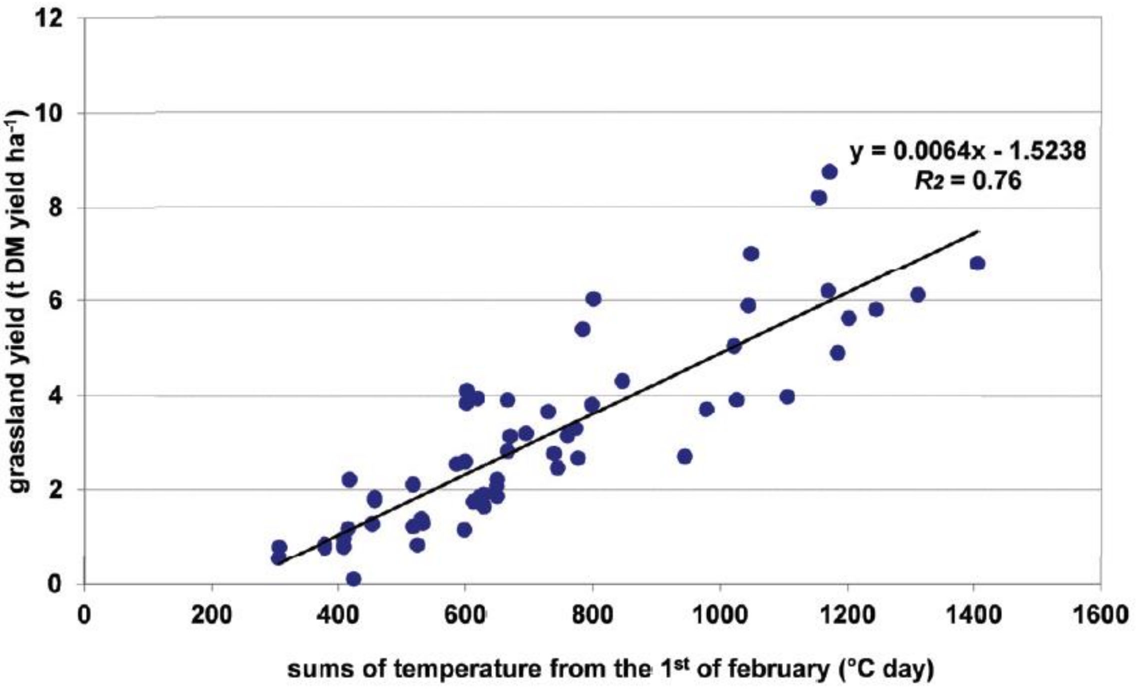


Figure 9 model of first production cycle, without fertilization; 10 meadows, in 2008 and 2009.

Feed balances
For purposes of farming systems research and collection of statistical data on regional levels, feed balances are often used to estimate grassland production.

Aarts et al. (2008) estimated grassland yields in the Netherlands at farm level using data on milk production, energy requirements, feed composition, and maize yields. The grassland yield was the output of the balance calculation. This methodology is now used by the Netherlands to report grassland yields to DG Environment. The net grass yields of a farm is generally not measured in practice. Grass is an internal product for a farm; it is produced and consumed. The net yield is therefore calculated from a feed balance. As a first step, the necessary amount of feed energy is calculated, on the basis of the numbers of animals present and the standard feed requirement per animal. The calculation procedure is similar to the one used for the calculation of excretions for the manure legislation (Tamminga et al., 2005). In the second step the energy in purchased feed is deducted from the total energy requirement of the farm. The purchase of feed is registered and often the energetic value is known. If that is not the case, use is made of normative values. The remaining energy need is assumed to be produced on the farm. The yield of forage maize and other non-grass forages are subtracted, after correction for conservation- and feeding losses. The forage maize yield is estimated by the farmer, contractor or farm advisor, at the time of the harvest. The dry matter yield is translated to energy yields with the help of silage analyses. Usually the average annual values of the analyses of a region are assigned to the relevant farms. The energy need that is not covered by purchased feed or home grown forages is assumed to be produced by grassland. Therefore, an error in the estimation of the forage yield has a large effect on the estimates of grass yield.
The distribution of the consumed grass-energy over silage and grazing pasture is derived from the grazing system. This procedure also corresponds to the calculation procedure for excretion of livestock. The calculated amount of grass silage is corrected for conservation and feeding losses. The sum of grazed grass and grass silage is the net grass yield, still in terms of energy. With the help of feed analysis, the energy yield is recalculated to a dry matter yield.

Table 8 Average grass yields in the Netherlands, calculated with the feed balance method.

	1998	1999	2001	2002	2003	2004	2005	2006	Mean
Grassland total									
DM (ton/ha)	10.7	10.9	10.2	10.4	9.5	10.2	10.2	9.2	10.2
Silage fraction (%)	70%	70%	74%	71%	72%	71%	73%	74%	72%
N (kg/ha)	351	347	306	310	276	313	281	265	306
Silage fraction (%)	63%	64%	68%	65%	64%	66%	69%	71%	66%
P (kg/ha)	43.6	42.0	39.2	41.6	35.3	39.4	38.4	32.9	39.1
Silage fraction (%)	68%	67%	70%	67%	68%	69%	70%	71%	69%

Kremer et al., (2009) described the feed balances for ruminants as used for estimation of excretion and grass yield for national and regional statistics in the Netherlands.
The diet of ruminants consists of silage grass and hay, silage maize, concentrates and meadow grass. The ratio between maize and grass in the diet is a major determinant of the mineral content in the excretion, due to the fact that the mineral content in maize is lower than in grass. In the South-East region (provinces Overijssel, Flevoland, Gelderland, Noord-Brabant & Limburg) silage maize forms a larger share in the diet of grazing animals than in the diet in the North-West region (provinces Groningen, Friesland, Drenthe, Utrecht, Noord-Holland, Zuid-Holland, Zeeland). Feed balances and excretion factors for ruminants are therefore differentiated for these two regions.
For ruminants which graze a part of the year on the meadow the feed balance also distinguishes a pasture season and a stable season, to estimate the amount of manure which is produced in the stable and on the pasture. Data on the length of the pasture season, and on the system of grazing in use (24h on meadow, at night in stable, 24h in stable) for the two regions are derived from a survey on grassland among very specialized dairy farms, specialized dairy farms and other grazing livestock holdings. Assumptions are made on the share of manure in the stable for each grazing system. This means that a significant part of the calculation of manure in the stable and on pastures (and therefore also the calculation of volatilization of nitrogen) is depending on these assumptions.

Feed balances are calculated with data on feed availability for ruminants in the region and their feed requirements.

- Data on regional availability of silage grass and hay is derived from an annual survey on grassland production among farmers with bovine animals.
- Data on the regional availability of silage maize is available from an annual survey among arable farmers on the harvest of arable products as well as from the survey on grassland production.
- Data on the regional use of concentrates by ruminants is available from national sales statistics and index numbers of the use of concentrates by different animal groups.
- Data on the consumption of meadow grass by ruminants in the Netherlands and in the regions is computed within the model.
- The average number of animals present during a year is based on the number of animals counted in the FSS (which will be corrected for years with major animal diseases). For sheep

and goats the FSS is not a good estimator of the number of sheep or goats present during the year, this will be corrected by the calculation of excretion factors.

The consumption of silage grass and hay, silage maize and concentrates is variable for dairy cows. For other ruminants the consumption of conserved roughage and concentrates is based on norms.

In the feed balance feed is expressed in “Voedereenheid Melk” (VEM), which is a measure for the feeding value of the feed for the production of milk. The feed requirement of dairy cows is depending on the average milk production of dairy cows and therefore varies between regions. The feed requirements of other ruminants are based on norms for feed requirements of different animal groups.

The feed requirement can also be expressed in VEM.

In Table 9 the calculation of a feed balance is presented. The numbers are corresponding to the steps which have to be followed;

1. The total amount of fodder available (except of meadow grass) is known from surveys, sales statistics, index numbers. The ruminants (except dairy cows) are on a fixed diet.
2. The consumption of meadow grass is determined from the feed requirement of the ruminants (except dairy cows) minus the consumption of the other feed components (concentrates, roughage).
3. From the total feed available for ruminants and the consumption by ruminants (except dairy cows) the consumption by dairy cows of fodder (except meadow grass) is calculated.
4. The consumption of meadow grass by dairy cows is calculated from the feed requirement of dairy cows and the consumption of the other feed components by dairy cows.
5. The total meadow consumption of meadow grass in the Netherlands is also estimated in the feed balance as the sum of the meadow grass consumption by dairy cows and by other ruminants.

Table 9 Calculation steps in feed balance (see text for explanation).

	Silage grass and hay	Silage maize	Meadow grass	Concentrates	kVEM per animal
Dairy cows	3	3	4	3	dependent on milk production
Other ruminants	1	1	2	1	fixed
Total	1	1	5	1	

The amount of minerals which is retained in the animal is depending on the production of animal products, and the mineral content per kg product. Data on milk and meat production are derived from statistics, where available. Statistics on the production and mineral contents of milk are derived from Productschap Zuivel and NRS.

The retention of minerals in the animal are calculated as;
(end weight * minerals in animal at end weight) – (start weight * mineral content at start weight).

Index numbers on animal growth, birth of young, the retention of minerals in ruminants etcetera are derived from research data from amongst others NRS, Animal Sciences Group, PV.

In Figure 10 it can be seen that the estimated grass intake during grazing has decreased over the years, especially in the South-East region. This can partly be explained by the increasing tendency of farmers to keep dairy cows in the stable all year long. However many researchers question the very low estimates of the past few years.

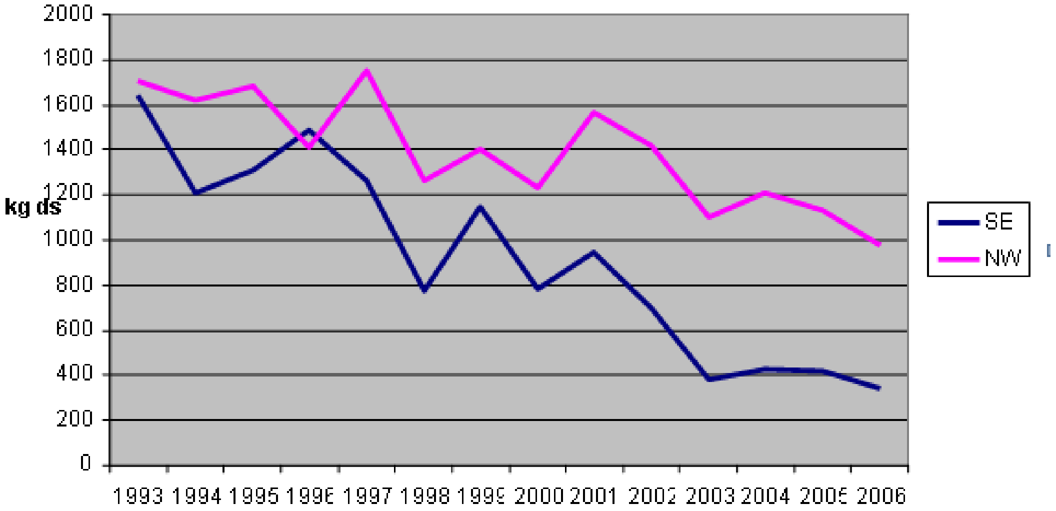


Figure 10 Estimated grazing intake per dairy cow (kg DM/year).

As the consumption of grass is a very important factor in calculating feed balances (which are used to estimate excretion), Kremer et al. (2009) have explored different sources which may cause the low estimation of meadow grass consumption. The underestimation of the consumption of meadow grass by ruminants and especially dairy cows in the two regions model may arise from an overestimation of the availability of silage grass and hay, silage maize or concentrates or an underestimation of the feed requirements and related problems. The possible sources causing an underestimation of the consumption of meadow grass have been discussed with experts from several research institutes:

- Feed requirements: the VEM model is a model from the Wageningen University and Research Centre in which the feed requirement of a dairy cow to produce one litre of milk is estimated. This model however does not take into account sickness or other inefficiencies. To account for these inefficiencies the WUM has decided to raise the feed requirement based on the VEM-model to 102%. This will result in a higher estimation of meadow grass and therefore total grass consumption.

- Animal numbers: the data on animal numbers are derived from the FSS. This number represents however the situation on the 15th of May. For the estimation of manure production and the excretion of minerals the average number of animals during a year is needed. For some animal groups the numbers of animals counted in the FSS do not present a good estimate of the average number of animals present in a year (for instance sheep and goats). This is taken into account. For some animals (horses and ponies), the FSS underestimates the real amount of animals present severely, however better estimates are not available. This means that the consumption of mainly hay by other ruminants than dairy cows is underestimated and therefore the uptake of hay by dairy cows overestimated. Hay is however a minor input in the feed balance, therefore the effect of the underestimation of horses and ponies on the calculation of excretion of minerals by dairy cows will be minimal.

- Consumption of roughage: another source which might cause an underestimation of the consumption of meadow grass might be the overestimation of the other feed components. The consumption of silage maize and silage grass is derived from annual surveys. The amount of grass produced and especially the part that is grazed is not easily measurable. The methods available are model calculations, field experiments and expert judgement. The WUM estimates the consumption of silage grass and hay with annual statistics from a survey and mineral contents from analyse data of a lab (BLGG). The consumption of meadow grass is however not easily measured. The consumption of meadow grass is estimated within the feed balance. For the main categories of ruminants the feed requirements are calculated on the basis of statistics taking into account milk production and growth. After being fed with the statistically observed quantities of other feed and forage available, the remaining feed requirement is calculated and it is assumed to equal the meadow grass consumption.

The advantages of using a feed balance model are:

- The method is fairly simple.
- The method is based on statistics. This implies that each year data become available and that these data are gathered following a documented and consistent methodology.
- The method takes account of farm management practices, fertiliser use, livestock density, feed and forage availability and varying soil production.
- Grass consumption is part of the feed consumed and therefore part of the minerals which end up in manure. On the other hand it is an output of the soil surface balance. This implies that inaccuracies in the calculation of grass consumption do not affect the surplus of the soil surface balance.

Basic data needs are:

- Statistics on the consumption of feedstuffs.
- Statistics on the consumption of forage (exclusive meadow grass).
- Feed requirements for all ruminants.
- Figures on mineral content and feeding value of feed, forage and meadow grass.

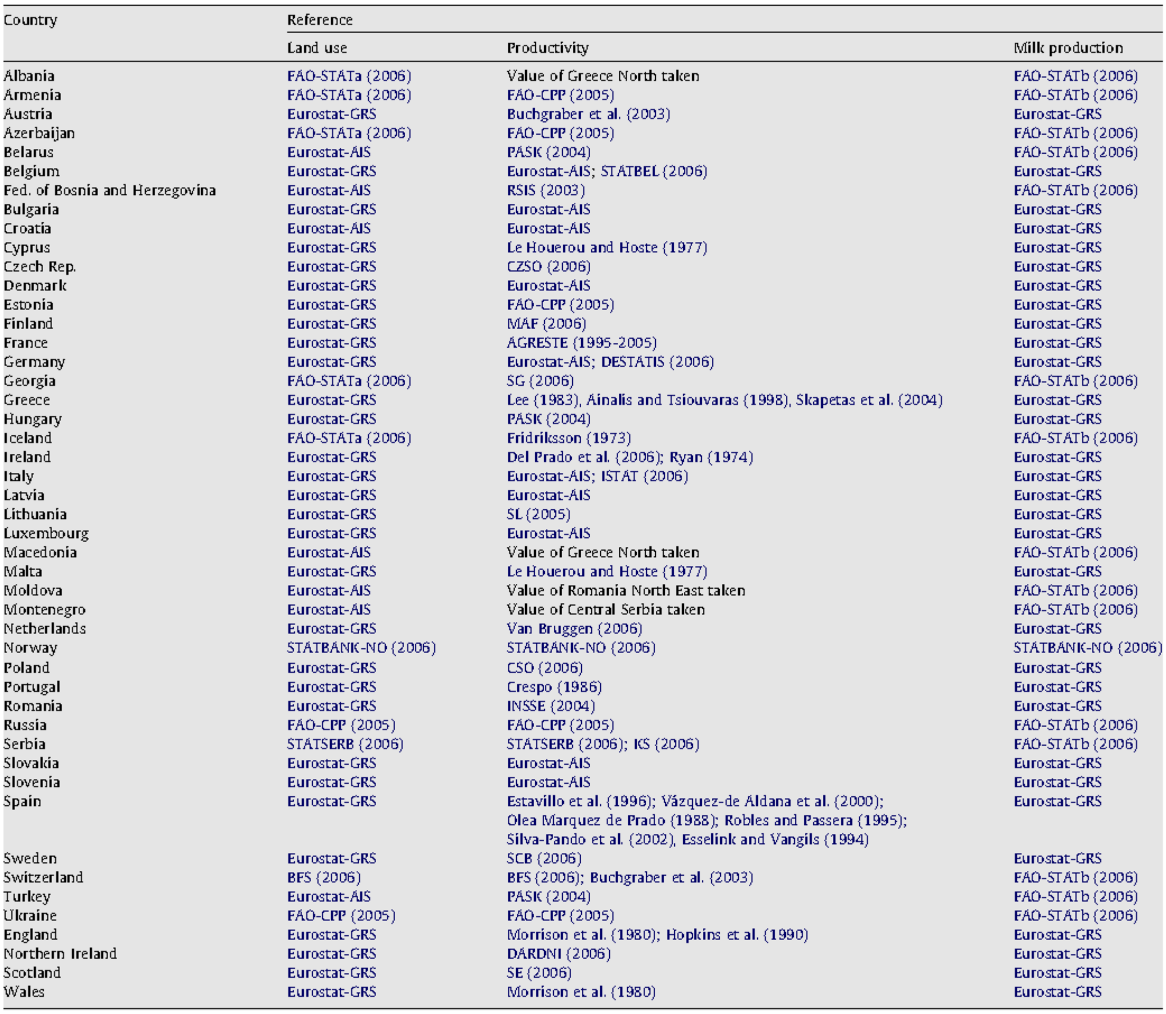
The estimated production of grassland by our feed balance model is difficult to compare with results from other research. Research on grassland production is carried out by many institutes. There is data on grassland production from field experiments on (research) farms. The production on research farms tends to be much higher than on the average farm in the Netherlands. In other approaches no data on grassland production is used, the total grassland production is estimated within the feed balance. The different approaches to estimate grassland production have been discussed with experts.

We prefer to make use of observed data (surveys) on grassland production above estimating the total grassland production within a model or from field experiments.

The reliability of the data on the consumption of silage grass, hay and silage maize (and thus the estimation of meadow grass consumption and excretion) is very depending on the quality of the survey. We have reviewed the questioning in the surveys which were carried out over the last couple of years and the impact of the used questioning on the results, for more information see Appendix 3. We have also improved the analysis and estimation of grassland production from the data of the survey.

Smit el al., (2008) estimated the spatial distribution of grassland productivity in Europe, using data from various regional, national and international census statistics for Europe, extending eastwards to the Ural Mountains (Table 10). Regional differences in grassland productivity were analysed considering selected climatic and agronomic parameters and were compared with the remotely sensed normalised difference vegetation index (NDVI) and simulations from two impact assessment models. Results show large regional differences in grassland productivity and land use in Europe (Figure 11). Grassland productivity is highly correlated with annual precipitation and less with annual temperature sum and growing season length. The correlation with NDVI is low. Comparison with large-scale simulations from two different models reveal that simulated spatial patterns of grassland productivity differ from the data obtained in this study (Figure 12), which may be attributable to the under-representation of management effects in these models.

Table 10 Reference-sources of the data collection on land use, grassland productivity and milk production (Smit et al., 2008)



Country	Reference		
	Land use	Productivity	Milk production
Albania	FAO-STATa (2006)	Value of Greece North taken	FAO-STATb (2006)
Armenia	FAO-STATa (2006)	FAO-CPP (2005)	FAO-STATb (2006)
Austria	Eurostat-GRS	Buchgraber et al. (2003)	Eurostat-GRS
Azerbaijan	FAO-STATa (2006)	FAO-CPP (2005)	FAO-STATb (2006)
Belarus	Eurostat-AIS	PASK (2004)	FAO-STATb (2006)
Belgium	Eurostat-GRS	Eurostat-AIS; STATBEL (2006)	Eurostat-GRS
Fed. of Bosnia and Herzegovina	Eurostat-AIS	RSIS (2003)	FAO-STATb (2006)
Bulgaria	Eurostat-GRS	Eurostat-AIS	Eurostat-GRS
Croatia	Eurostat-AIS	Eurostat-AIS	Eurostat-GRS
Cyprus	Eurostat-GRS	Le Houerou and Hoste (1977)	Eurostat-GRS
Czech Rep.	Eurostat-GRS	CZSO (2006)	Eurostat-GRS
Denmark	Eurostat-GRS	Eurostat-AIS	Eurostat-GRS
Estonia	Eurostat-GRS	FAO-CPP (2005)	Eurostat-GRS
Finland	Eurostat-GRS	MAF (2006)	Eurostat-GRS
France	Eurostat-GRS	AGRESTE (1995-2005)	Eurostat-GRS
Germany	Eurostat-GRS	Eurostat-AIS; DESTATIS (2006)	Eurostat-GRS
Georgia	FAO-STATa (2006)	SG (2006)	FAO-STATb (2006)
Greece	Eurostat-GRS	Lee (1983), Ainalis and Tsiouvaras (1998), Skapetas et al. (2004)	Eurostat-GRS
Hungary	Eurostat-GRS	PASK (2004)	Eurostat-GRS
Iceland	FAO-STATa (2006)	Fridriksson (1973)	FAO-STATb (2006)
Ireland	Eurostat-GRS	Del Prado et al. (2006); Ryan (1974)	Eurostat-GRS
Italy	Eurostat-GRS	Eurostat-AIS; ISTAT (2006)	Eurostat-GRS
Latvia	Eurostat-GRS	Eurostat-AIS	Eurostat-GRS
Lithuania	Eurostat-GRS	SL (2005)	Eurostat-GRS
Luxembourg	Eurostat-GRS	Eurostat-AIS	Eurostat-GRS
Macedonia	Eurostat-AIS	Value of Greece North taken	FAO-STATb (2006)
Malta	Eurostat-GRS	Le Houerou and Hoste (1977)	Eurostat-GRS
Moldova	Eurostat-AIS	Value of Romania North East taken	FAO-STATb (2006)
Montenegro	Eurostat-AIS	Value of Central Serbia taken	FAO-STATb (2006)
Netherlands	Eurostat-GRS	Van Bruggen (2006)	Eurostat-GRS
Norway	STATBANK-NO (2006)	STATBANK-NO (2006)	STATBANK-NO (2006)
Poland	Eurostat-GRS	CSO (2006)	Eurostat-GRS
Portugal	Eurostat-GRS	Crespo (1986)	Eurostat-GRS
Romania	Eurostat-GRS	INSSE (2004)	Eurostat-GRS
Russia	FAO-CPP (2005)	FAO-CPP (2005)	FAO-STATb (2006)
Serbia	STATSERB (2006)	STATSERB (2006); KS (2006)	FAO-STATb (2006)
Slovakia	Eurostat-GRS	Eurostat-AIS	Eurostat-GRS
Slovenia	Eurostat-GRS	Eurostat-AIS	Eurostat-GRS
Spain	Eurostat-GRS	Estavillo et al. (1996); Vázquez-de Aldana et al. (2000); Olea Marquez de Prado (1988); Robles and Passera (1995); Silva-Pando et al. (2002), Esselink and Vangils (1994)	Eurostat-GRS
Sweden	Eurostat-GRS	SCB (2006)	Eurostat-GRS
Switzerland	BFS (2006)	BFS (2006); Buchgraber et al. (2003)	FAO-STATb (2006)
Turkey	Eurostat-AIS	PASK (2004)	FAO-STATb (2006)
Ukraine	FAO-CPP (2005)	FAO-CPP (2005)	FAO-STATb (2006)
England	Eurostat-GRS	Morrison et al. (1980); Hopkins et al. (1990)	Eurostat-GRS
Northern Ireland	Eurostat-GRS	DARDNI (2006)	Eurostat-GRS
Scotland	Eurostat-GRS	SE (2006)	Eurostat-GRS
Wales	Eurostat-GRS	Morrison et al. (1980)	Eurostat-GRS

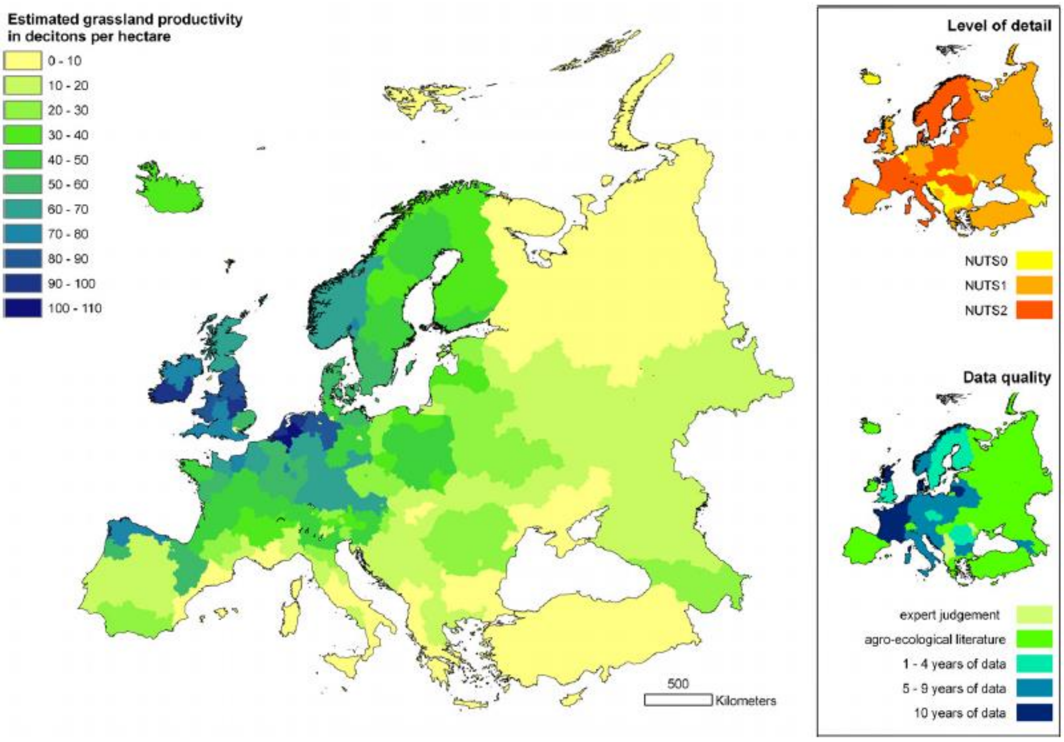


Figure 11 Spatial distribution of grassland productivity (dt ha1) in Europe. NUTS, Nomenclature of Territorial Units for Statistics (Smit et al., 2008).

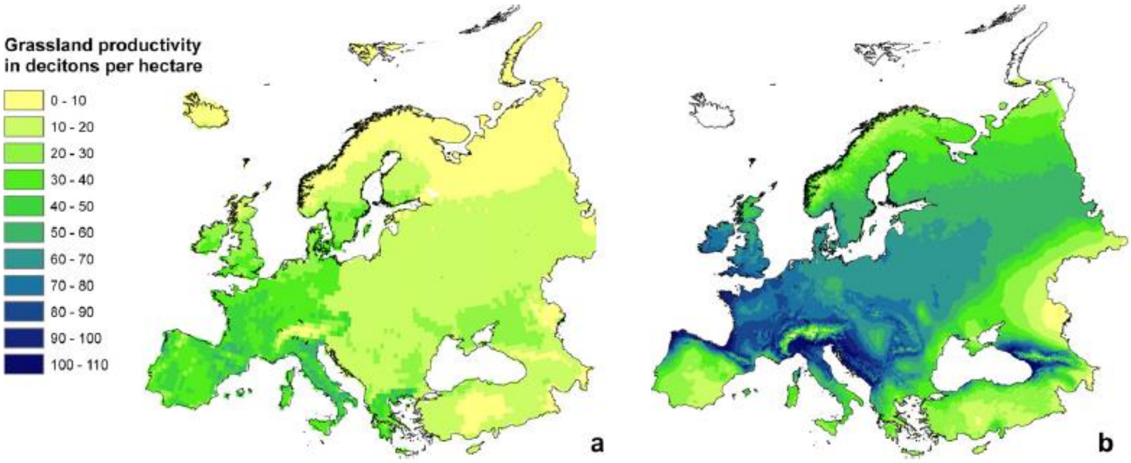
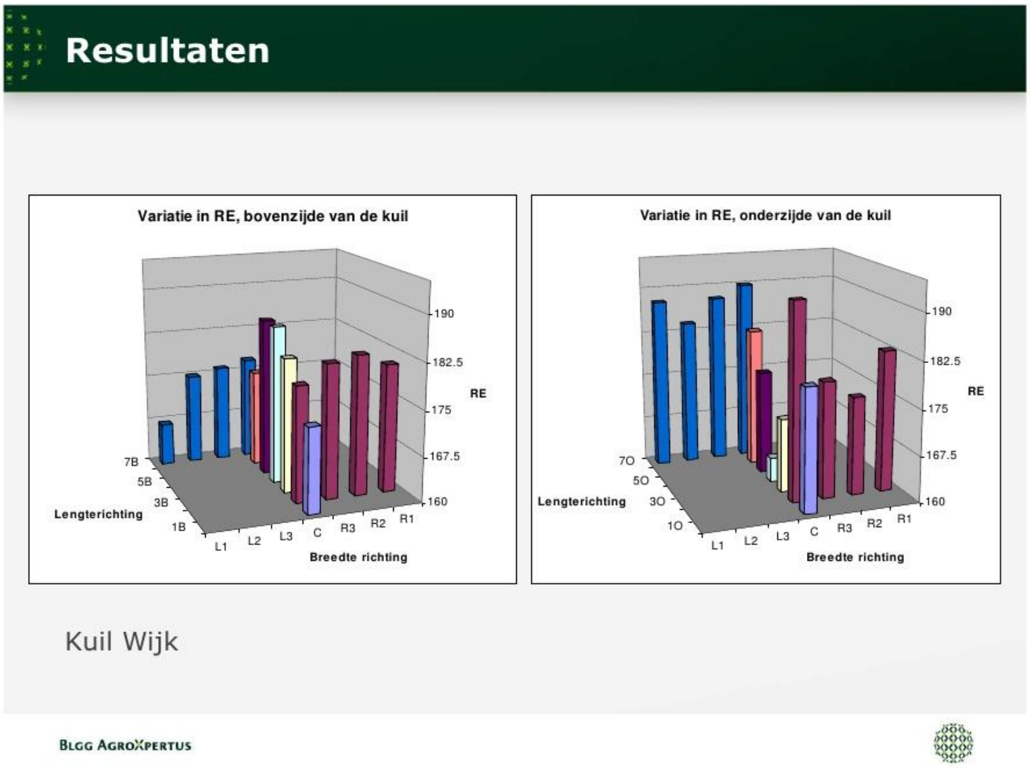


Figure 12 Model simulations of (a) actual grassland productivity in Europe from IMAGE 2.4 (Bouwman et al., 2006) and of (b) potential rain-fed productivity at low input conditions from AEZ (Fischer et al., 2002). Note that actual yields from IMAGE represent the grassland yield used for feedstuff while simulations by the AEZ model refer to rain-fed yields that are potentially available. Important is that the spatial yield patterns slightly differ among models and are considerably different from the yield statistics presented in Figure 11.

2.3 Measuring nutrient content in grasses

2.3.1 Destructive measurement

Sampling
It is important to take a representative sample of grass for analysis of N and P contents, because spatial variability of contents may be high in a field. The spatial variability will be highest in natural or extensively managed grassland with a large diversity of grass species, grazed grassland (with locally high contents of N and P, related to urine patches and dung pats), and fields on farms. The spatial variability will be much smaller in well-managed plots (of relatively small size) in controlled field experiments.
In cut grassland, samples can be taken from the cut grass. In grazed grassland, samples should be taken at different intervals and different sites in the field during the grazing period to obtain an average value of the N and P contents of the grass consumed by the livestock. In natural or extensively managed grasslands, samples should be taken that are representative for the species found in the specific field. Besides harvesting parts of the grassland area by mowing, also individual plants can be sampled. Kara (1998) recommended for hay, pasture and forage grass to take 40-50 plants, and to sample the fourth uppermost leaf blades. A third way of sampling, is that not the grass in the field is sampled, but grass in the silage pit or stored hay. It must be noted that some N will be lost during silage and storage of hay. Samples should be taken in different places in the silage pit and stored hay to representative samples for the whole harvest. Figure …. shows the heterogeneity of the crude protein content in a grass silage pit.



Resultaten

Kuil Wijk

BLGG AgroXpertus

Figure. Results of variation of the protein content in grass silage pit. Left figure presents the upper part of the pit and right figure the lower part. Lengte richting = length; breedte richting = width; RE = crude protein *content).* (Source: BLGG AgroXpertus, the Netherlands http://www.slideshare.net/BLGGAgroXpertus/variatie-in-de-kuil-2010#btnNext)

Sampling, handling and preparation

Plant samples should always dried as soon as possible or stored at cool conditions in order to minimize respiration and decomposition. Fresh plant tissue should be placed in open, clean paper bags, partially air-dried if possible, or kept in a cool environment during shipment to the laboratory (Kara, 1998). Fresh plant tissue should not be placed in closed plastic bags unless the tissue is either air-dried or the bag and contents are kept cool.

Drying is best carried out at 60–80 °C in a well-ventilated drying oven (often withn 24 hours). Enzymes present in plant tissue will be inactive at temperatures above 60 °C. Drying temperatures above 80°C may result in thermal decomposition and reduction in dry weight). Only air drying at room temperature may not stabilize samples and prevent enzymatic decomposition. Samples should, therefore, be properly dried as soon as possible after taking the sample.

The dried plant samples are then finely ground (should pass a 1 mm sieve) in order to obtain a homogeneous sample from which representative subsamples can be taken.

After particle size reduction and homogenization, samples should be stored in a cool and dry place in tightly closed flasks or bags, protected agains sun light. Dry samples can be stored for at least 10 years (Houba et al., 1995).

Determination of dry matter content

The dry matter content of a plant sample is determined by the gravimetric loss of water at drying at 105 °C for 2 hours. The dry-matter content is used to correct the concentration in a sample dried at 70-80 °C to an absolute dry-matter basis. Drying at 105 °C can change the chemical composition of plant material, so that samples dried at 105 °C should not be used for chemical analysis.

Organic matter destruction and chemical analysis

Plant tissue samples previously dried, ground, and weighed are prepared for elemental analysis through decomposition/destruction of organic matter. The two commonly used methods of organic matter destruction are dry ashing (high-temperature combustion) and wet ashing (acid digestion). Both methods are based on the oxidation of organic matter through the use of heat and/or acids (Kara, 1998; Temminghoff et al., 2000).

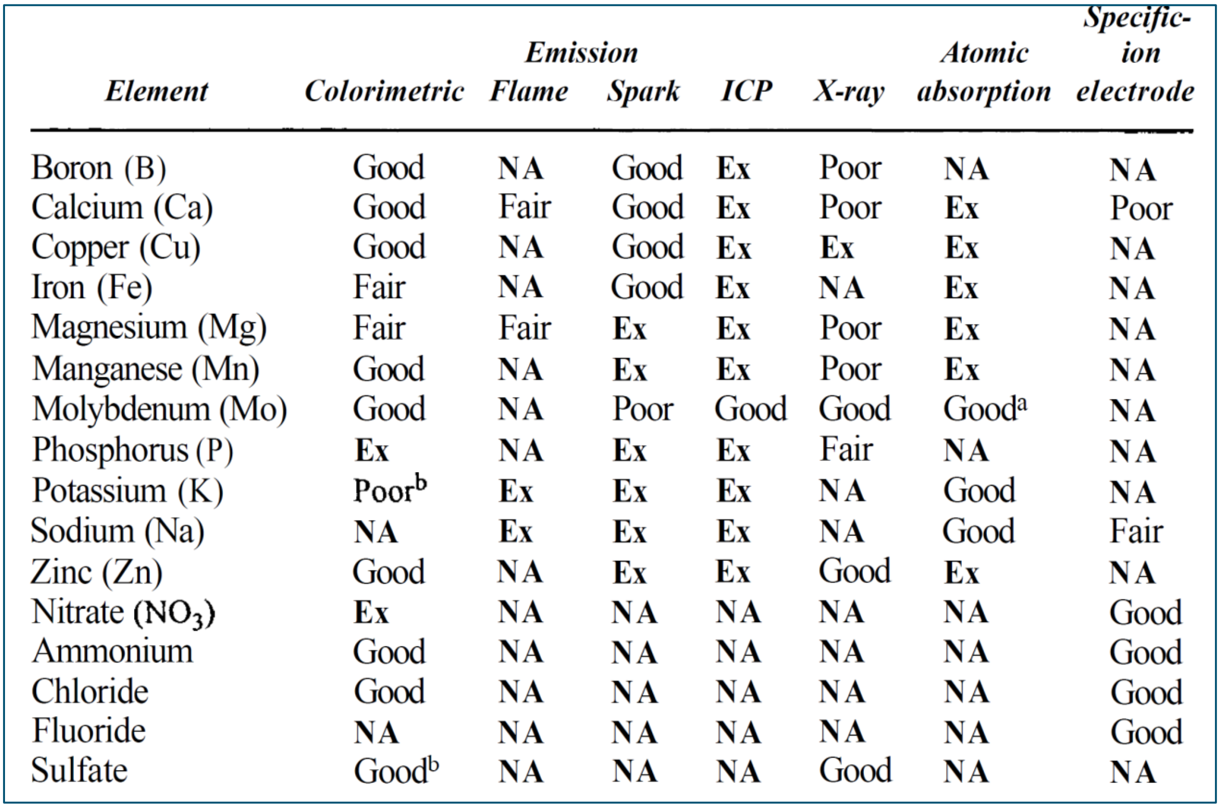
Dry ashing is conducted in a muffle furnace at temperatures of 500 to 550 °C for 4 to 8 hours. At the end of the ashing period, the vessel is removed from the muffle furnace, cooled, and the ash is dissolved in acid(s). Wet digestion involves the destruction of organic matter through the use of both heat and acids. Hot plates or digestion blocks are frequently used to maintain temperatures of 80 to 125^{0}C. Sometimes microwaves heating is used (microwave digestion). The Kjeldahl method is a well-known wet oxidation method to determines NH_4 and protein N in plant tissues. It is based on the wet oxidation of organic matter using sulphuric acid and a digestion catalyst. The Kjeldahl procedure has several variances, mainly micro and macro, based primarily on sample size and required apparatus.

After digestion is complete and the sample is cooled, dilutions are made to meet analytical requirements. Wet digestion samples can be used for analyses of N and P (and other elements) and dry ashing and microwave digestion for P (and other elements). The analysis of NH_4 after wet digestion can be performed by a colorimetric method (including a segmented-flow analysis) or ammonium electrode (Table). P can be determined in wet digestion sample by a colorimetric method (including a segmented-flow analysis). P can also be determined in the sample from dry ashing and microwave digestion using inductively coupled plasma (ICP) techniques, such as ICP optical emission spectrometry (ICP-OES).

Dumas devised a method for total N, using combustion. This method is applied in automated combustion method determines the amount of N in all forms (NH_4, NO_3, protein, and heterocyclic N) in plant tissues using an induction furnace and a thermal conductivity detector (Hansen, 1989).

The choice for the analytical method depends on the available equipment and the elements that have to be analysed.

Table. Suitability of some of the commonly used nalytical techniques for elemental and ion determination in prepared plant tissue extracts, digests, and ash solutions.
NA = not applicable; Ex = excellent (high sensitivity with minimal interference); Good = moderate sensitivity with some interference; Fair = reasonable sensitivity, but with matrix effects; Poor = reasonable sensitivity with significant matrix effects.



		Emission					Specific-ion
Element	Colorimetric	Flame	Spark	ICP	X-ray	Atomic absorption	electrode
Boron (B)	Good	NA	Good	Ex	Poor	NA	NA
Calcium (Ca)	Good	Fair	Good	Ex	Poor	Ex	Poor
Copper (Cu)	Good	NA	Good	Ex	Ex	Ex	NA
Iron (Fe)	Fair	NA	Good	Ex	NA	Ex	NA
Magnesium (Mg)	Fair	Fair	Ex	Ex	Poor	Ex	NA
Manganese (Mn)	Good	NA	Ex	Ex	Poor	Ex	NA
Molybdenum (Mo)	Good	NA	Poor	Good	Good	Good[a]	NA
Phosphorus (P)	Ex	NA	Ex	Ex	Fair	NA	NA
Potassium (K)	Poor[b]	Ex	Ex	Ex	NA	Good	NA
Sodium (Na)	NA	Ex	Ex	Ex	NA	Good	Fair
Zinc (Zn)	Good	NA	Ex	Ex	Good	Ex	NA
Nitrate (NO_3)	Ex	NA	NA	NA	NA	NA	Good
Ammonium	Good	NA	NA	NA	NA	NA	Good
Chloride	Good	NA	NA	NA	NA	NA	Good
Fluoride	NA	NA	NA	NA	NA	NA	Good
Sulfate	Good[b]	NA	NA	NA	Good	NA	NA

2.3.2 Non-destructive measurement

Chlorophyll meter
The strong positive relationship between leaf chloropyll content and leaf N concentration can be used for predicting crop N status. Hand-held chlorophyll meters (SPAD) permit an in situ rapid and non-destructive determination of leaf chlorophyll content by measuring leaf transmittance. However, chlorophyll meter readings

are affected by crop cultivar (and grass species), stage of growth, soil moisture status, and nutrients other than N. Chlorophyll meters can used for detecting the need for N fertilizer application. Chlorophyll meters have their greatest sensitivity in the deficient to adequate range of N nutrition (Figure). Gáborèík (2001) showed in a study in Slovakia that there was decreasing tendency for grass species in SPAD values: fescue > timothy > coocksfoot > ryegrass. A similar order was found for crude protein concentration: fescue > cooksfoot > timothy > ryegrass (Table). The results indicated that there was a relationship between SPAD values of individual species and crude protein content. Chlorophyll meters can be used to determine N concentration in grassland for specific conditions. Site-specific and grass-land specific calibration procedures are needed.

Table. SPAD readings, determined (CP) and calculated (CP´) crude protein content (mg g^{1}) of four grass species (Gáborèík, 2001).

Species	Parameters			Species	Parameters		
Timothy cultivars	SPAD	CP	CP´	**Ryegrass cultivars**	SPAD	CP	CP´
VV/II/85	46.2	189.4	193.4	Kentaur	35.2	165.2	143.2
Kaba	46.1	191.4	193.1	Kerem	30.2	121.2	128.4
Vì trov	40.3	188.2	176.3	Quickstar	41.8	157.0	162.7
Bartimo	38.2	169.7	165.4	Sakiki	33.2	143.6	137.3
G/H/	39.4	172.1	173.0	Gator	379	165.0	151.1
Feriol (WL)	35.0	154.1	159.8	Numan	36.2	116.2	145.5
Cooksfoot cultivars	SPAD	CP	CP´	**Fescue cultivars**	SPAD	CP	CP´
DP-65 05	36.3	172.3	161.8	FP-4	37.8	154.4	171.2
Rela	44.1	186.3	188.3	Premil	38.6	186.7	173.5
Lada	46.9	186.8	198.7	Roznovska	38.8	174.0	174.0
Vega	46.0	210.3	195.5	Bundy	40.5	184.0	178.9
Lemba	41.1	189.7	178.5	Szarvasi	45.6	210.0	193.5
Baraula	38.6	147.9	169.8	Swift	47.7	185.0	195.5

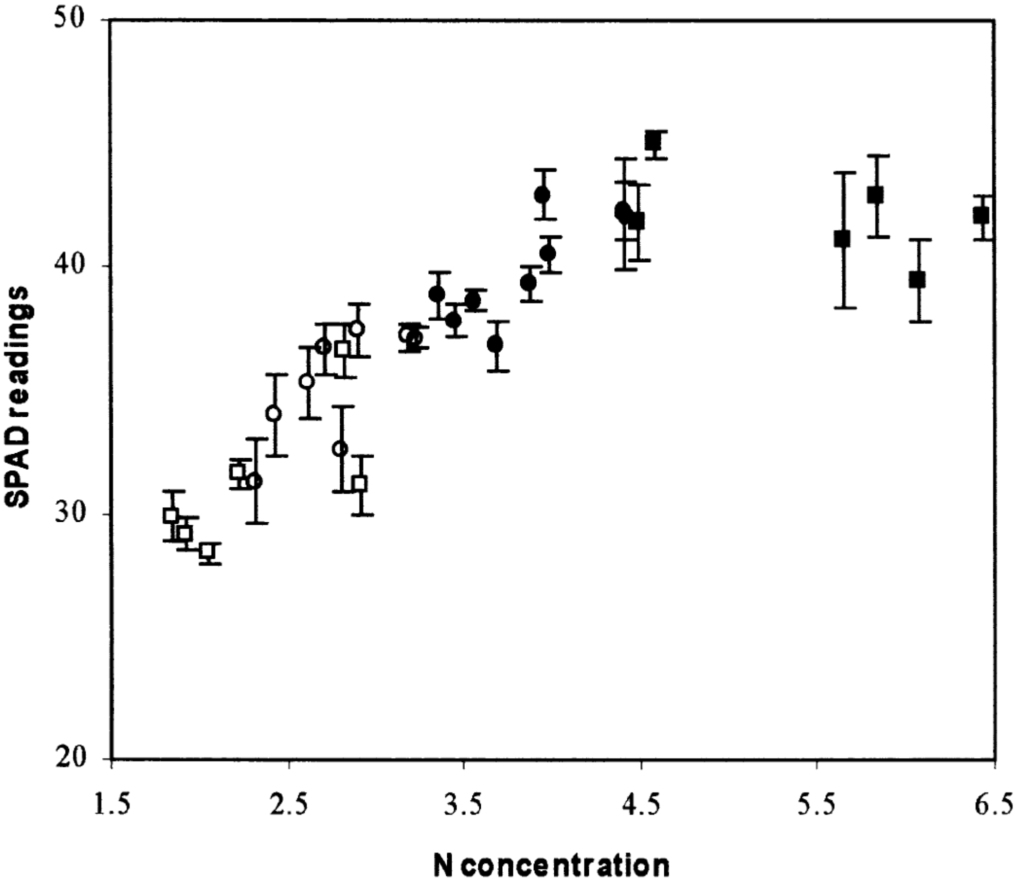


Figure. Measured leaf N concentrations in cocksfoot sward against readings with a SPAD chlorophyll meter in a study in France. (Duru, 2002).

Near infrared reflectance spectrometry

With near infrared reflectance spectrometry (NIRS) monochromatic light is directed at the plant tissue sample. Diffuse light is deflected from the sample and detected by lead sulfide detectors. The instrument is most often used to determine the content of protein. In order to calibrate the NIR instrument, it is necessary to determine the same parameters via wet chemistry on a large population of samples. The major advantage of NIR is that the analysis is non-destructive, simple and very rapid.

A method for measuring N concentration in perennial ryegrass and red fescue based on NIRS was developed. N concentrations in the range from 0.6 to 6.26% N could be predicted with an RMSEP of 0.19–0.24% N using PLSR models on raw and scatter corrected NIR spectra. However, samples from more years need to be included in the calibration data in order to increase the robustness of the models. The RMSEP corresponds to a higher measuring error than the reproducibility of the Dumas method, but the NIRS method developed is sufficiently accurate and precise to replace Dumas for evaluation of the plant N status in a field in practical seed production. Accordingly the method developed can be of great value for fast and cheap determinations of N concentration in the future, when novel N application strategies based on measurement of the plant N concentration are developed and when N budgets are introduced in grass seed production.

Gislum et al. (2004) Measurements of nitrogen (N) concentrations in plant samples are increasingly being used to support the development of novel N application strategies, which are based on actual plant N concentration as well as introduction of N budgets in agriculture. In order to meet the increasing demands for N measurements, the development of a fast and cheap, but still reliable technique is required. In the present study it was accordingly investigated whether near-infrared spectroscopy (NIRS) can be implemented for measurement of N concentration in grass samples. From 2000 to 2002 a total of 837 plant samples were collected from different field trials on 12 sampling sites in Denmark. The sample set consisted of 17 cultivars of red fescue (*Festuca rubra* L.) and perennial ryegrass (*Lolium perenne* L.) with a range in N concentration from 0.6 to 6.26% N. Visual-NIRS measurements (400–2498 nm) were performed on the dried, ground samples and plant N concentrations were measured using the Dumas method. Partial least squares regression models were developed on the near-infrared (NIR) spectra (1100–2498 nm) and the N concentrations in the dry grass samples with the aim of predicting the N concentration in samples not contained in the models. Models on raw and scatter corrected spectra gave root mean square error of prediction, RMSEP=0.19–0.24% N and correlation coefficients, R=0.97–0.98, when tested on an independent test set of samples from all harvest years, whereas models tested on samples from a harvest year not included in the calibration gave RMSEP=0.23–0.35% N and R=0.95–0.99. The prediction error is higher than the reproducibility of the Dumas method, but the NIRS method developed can still be used for measuring the N concentration in samples of perennial ryegrass and red fescue with sufficient precision and accuracy for practical use. Studies of the year effect showed that samples from more years needs to be included in the calibration data in order to increase the robustness of the model.

Ward et al. (2011) A near infrared reflectance spectroscopy (NIRS) method for rapid determination of nitrogen, phosphorous and potassium in diverse meadow grasses was developed with a view towards utilizing this material for biogas production and organic fertilizer. NIRS spectra between 12,000 cm−1 and 4,000 cm−1 were used. When validated on samples from different years to those used for the calibration set, the NIRS prediction of nitrogen was considered moderately useful with R2 = 0.77, ratio of standard error of prediction to reference data range (RER) of 9.32 and ratio of standard error of prediction to standard deviation of reference data (RPD) of 2.33. Prediction of potassium was less accurate, with R2 = 0.77, RER of 6.56 and RPD of 1.45, whilst prediction of phosphorous was not considered accurate enough to be of any practical use. This work is of interest from the point of view of both the removal of excess nutrients from formerly intensively farmed areas and also for assessing the plant biomass suitability for conversion into carbon neutral energy through biogas production.

This work has shown that nitrogen in dried and ground meadow grass can successfully be quantified by NIRS. However, the prediction of potassium by NIRS was only suitable for simple screening of high and low values.

Phosphorous prediction was not successful. These findings are of interest from both a nutrient removal and a bioenergy view point. Although only nitrogen prediction was classified as moderately useful, nitrogen is the main parameter of interest for biogas production, and an estimation of the mineral fertilizer value after treatment in a biogas plant is also of high interest, to optimize the subsequent use of fertilizer.

2.3.3 Remote sensing

Strong correlations exist between data from satellite imagery and the concentration of many biochemicals within vegetation canopies (Jago et al., 1999; Curran et al., 1997). The concentration of chlorophyll within a vegetation canopy is positively related to the point of maximum slope at wavelengths between 690 nm and 740 nm in reflectance spectra (Miller et al., 1990). This point is known as the “red edge” of plant reflectance, and characterizes the effective boundary between the strong absorption of red radiation by chlorophyll and the increased multiple scattering of radiation in near-infrared wavelengths (Curran et al., 1990; 1991). Researchers have also used the red edge–chlorophyll concentration relationship to explain the movement of the red edge to shorter wavelengths as a result of senescence or stress-induced chlorosis (Schutt et al., 1984). Therefore, information on the REP provides a useful indicator of canopy chlorophyll concentration, which can be used as an indicator of vegetation stress, photosynthetic capacity, development stage and productivity and nitrogen content (Curran et al., 1990) .There was a strong correlation (r=0.82) between nitogen (N) addition and chlorophyll concentration at the field site (Jago et al., 1999). Mutanga and Skidmore (2007) als showed that an increase in nitrogen supply yielded a shift in the red edge position to longer wavelengths. The red edge position, amplitude, slope at 713 nm and slope at 725 nm were significantly correlated to measured nitrogen concentration (bootstrapped r=0.89, −0.28, 0.63 and 0.75, respectively) even at canopy level (Mutanga and Skidmore, 2007). He and Mui (2010) summarized methods used to scale biochemical information from the leaf level to canopy level. For semi-arid heterogeneous grasslands they conclude that all methods are useful, but none are ideal. Clevers and Kooistra (2012) showed for their Dutch study sites that the $CI_{red\ edge}$ (red-edge chlorophyll index) was found to be a good and linear estimator of canopy N content for both the grassland site (R0.77) and for the potato field (R=0.88) . The approach they used can be applied with e.g. MERIS and Hyperion data and with the upcoming Sentinel-2 and -3 systems.

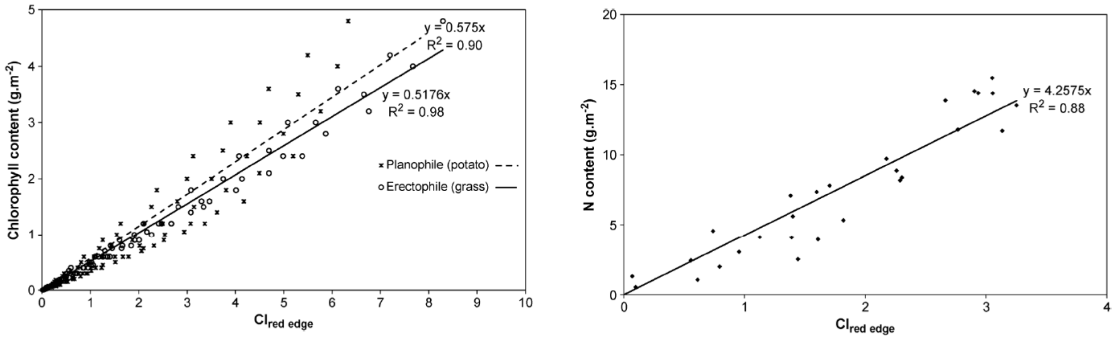


Figure 13 Relationship between CIred edge and (left) chlorophyll content for an erectophile and planophile leanf angle distribution, and (right) N content for the potato study site when omitting observations of potential luxury consumption for measured N contents above 15 g/m^2.

3 Biological nitrogen fixation

3.1 The nitrogen fixation process

Biological nitrogen fixation is a process only carried out by prokaryotic microorganisms. Many nitrogen-fixing bacteria can achieve nitrogen fixation on their own as free-living heterotrophic and autotrophic organisms, whereas others must establish a symbiotic relationship with a eukaryote host to support nitrogen fixation (Figure 14). The capacity to fix nitrogen in a symbiotic association with plants is found in three major groups of microbes: the root nodule bacteria (Rhizobiuni, Bradyr-hizobium, Sinor-hizobium, Azorhizobium), actinomycetes (Fmnkia) and cyanobacteria (Aizabaena, Nostoc). The major amount of fixed nitrogen is contributed by legume symbioses. Nitrogen-fixing legumes are significant components of many agricultural systems, and nodulated legumes contribute the majority of the biologically-fixed nitrogen supplied to both temperate and tropical agricultural systems.

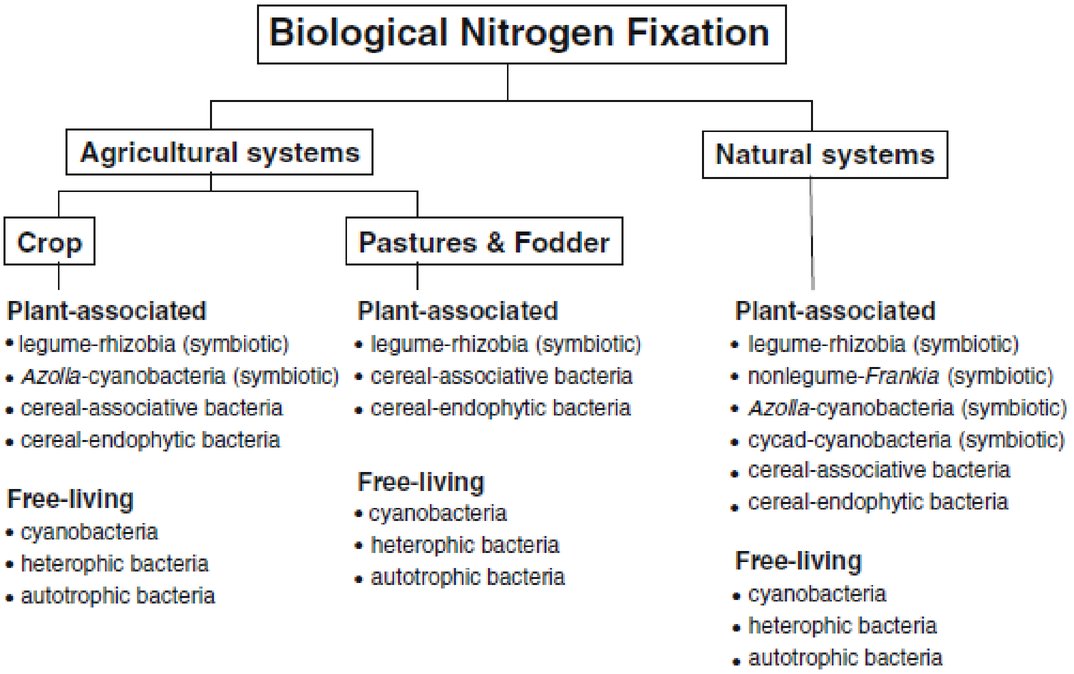


Figure 14 Biological nitrogen fixing agents in agricultural and terrestrial natural systems (Herridge et al., 2008).

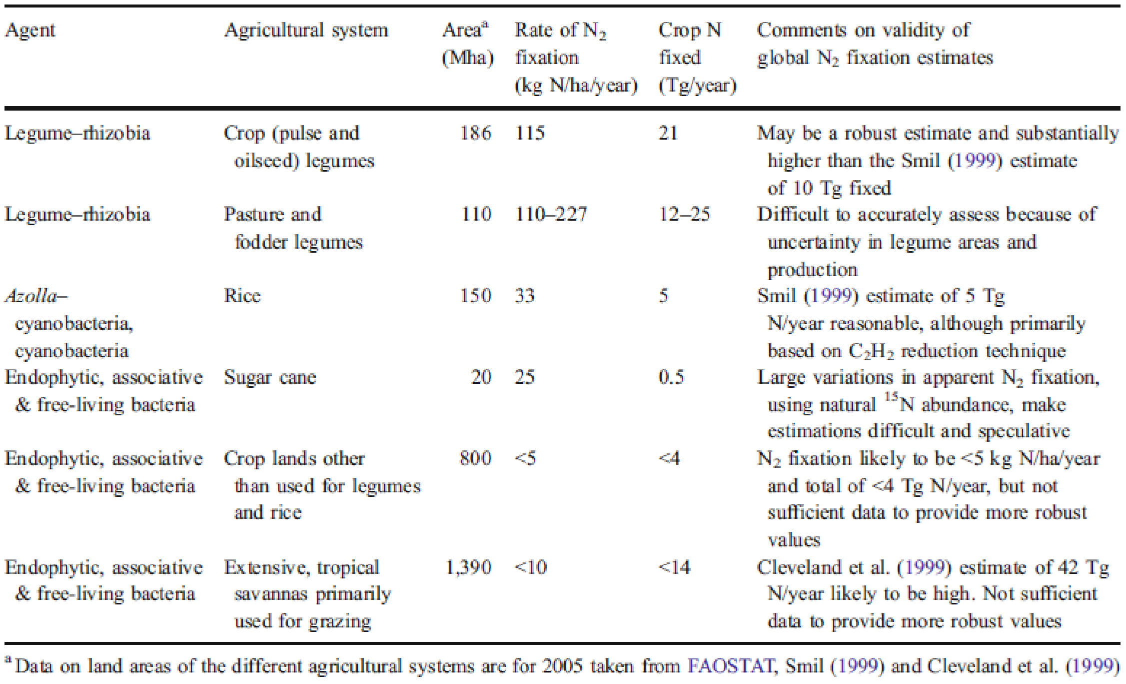
This study focuses on nitrogen fixation in plant associated pastures and fodder crops, i.e. the mutualistic interaction between rhizobia and legumes. Rhizobium is a soil bacterium that lives in nodules induced to grow on the root hairs of leguminous plants. The rhizobium bacteria fix atmospheric nitrogen, making it available to the legume as ammonium. With symbiotic fixation, significant net transfer of photosynthetically fixed plant carbon (C) to the N-fixing bacteria occurs, concurrently with net transfer of biologically fixed N directly from the bacteria to the host plant. With legumes, this all happens in highly specialised structures called nodules, which contain the bacteria and are formed on the roots or stems of the plants (Unkovich et al., 2008). Some of this nitrogen is transferred to non-legumes in the plant community through several mechanisms (Gibson, 2009):

1. decomposition of donor plant debris
2. shedding off of dead tissue and subsequent uptake of mineralized nitrogen
3. mycorrhizal connections
4. uptake of nitrogen from legume root exudates

In addition to these direct transfer routes, indirect nitrogen transfer through animals can be an important route. Legume nitrogen ingested by grazing animals is partly excreted in urine and faeces, after which it is available for plant uptake. The animal route also applies for housed animals that are fed on hay or silage containing legumes.

The supply of soil or fertilizer nitrogen has a distinct effect on nitrogen fixation (Marschner, 1986). Low levels of soil or fertilizer nitrogen enhance fixation due to a lag phase between infection and the onset of fixation. A shortage of nitrogen in this phase is detrimental to the formation of a source leaf area that is sufficiently large to supply photosynthates needed for nodule growth and activity. When the levels of combined nitrogen increase, nitrogen fixing capacity rapidly decreases. Shoot growth however continues to increase, but now based on inorganic nitrogen supply.

Table 11 Summary of estimates of N fixed annually in agricultural systems by rhizobia in symbiosis with crop, pasture and fodder legumes, numerous genera of bacteria associated with non-leguminous species and free-living bacteria (Herridge et al., 2008).



Agent	Agricultural system	Area[a] (Mha)	Rate of N_2 fixation (kg N/ha/year)	Crop N fixed (Tg/year)	Comments on validity of global N_2 fixation estimates
Legume–rhizobia	Crop (pulse and oilseed) legumes	186	115	21	May be a robust estimate and substantially higher than the Smil (1999) estimate of 10 Tg fixed
Legume–rhizobia	Pasture and fodder legumes	110	110–227	12–25	Difficult to accurately assess because of uncertainty in legume areas and production
Azolla–cyanobacteria, cyanobacteria	Rice	150	33	5	Smil (1999) estimate of 5 Tg N/year reasonable, although primarily based on C_2H_2 reduction technique
Endophytic, associative & free-living bacteria	Sugar cane	20	25	0.5	Large variations in apparent N_2 fixation, using natural ^{15}N abundance, make estimations difficult and speculative
Endophytic, associative & free-living bacteria	Crop lands other than used for legumes and rice	800	<5	<4	N_2 fixation likely to be <5 kg N/ha/year and total of <4 Tg N/year, but not sufficient data to provide more robust values
Endophytic, associative & free-living bacteria	Extensive, tropical savannas primarily used for grazing	1,390	<10	<14	Cleveland et al. (1999) estimate of 42 Tg N/year likely to be high. Not sufficient data to provide more robust values

[a] Data on land areas of the different agricultural systems are for 2005 taken from FAOSTAT, Smil (1999) and Cleveland et al. (1999)

3.2 Measuring nitrogen fixation

There are several sources of biological N fixation, i.e. the fixation by free living soil bacteria, clover in grasslands, and other leguminous crops. The N fixed by free living soil bacteria is generally small, i.e. < 5 kg N per ha per year; Paul and Clark, 1996).

The amount of N fixed by clover is difficult to estimate, because both the estimate of the average share of clover in grassland in a region and the amount of N fixed by clover are uncertain. If clover is grown on soils that contain mineral N (e.g. because of N fertilizer or manure application), clover can use this N and may not or slightly fix atmospheric N. In that case, not all N of the clover should be included in the gross N balance calculations. Only the biologically fixed N has to be included in gross N balance, because this N is “new” N in the N balance. The best estimate of N fixed by clover can be made from local experts with knowledge of the grasslands and management of grassland.

Improved quantification of legume biological nitrogen fixation (BNF) will provide better guidance for farmers on managing N to optimise productivity and reduce harmful losses to the environment. There are many techniques available for the direct quantitative measurement of legume BNF in the field and in controlled environments. However, these are time-consuming and therefore expensive, and generate data relevant only to the time and place of measurement. Alternatively, legume BNF can be estimated by either empirical models or dynamic mechanistic simulation models. Basic methodologies that are available to quantify biological N fixation are (Herridge et al., 2008):

- The enzyme nitrogenase, universally responsible for biological N fixation, is also capable of reducing acetylene (C2H2) to ethylene (C2H4). Both gases can be readily detected and quantified using gas chromatography.
- The total N-balance method is based on the principal that the plant/soil system will accumulate N over time if there is an input of N fixation. However, measures of N fixation may be underestimated because of N losses from the system during the period of study through ammonia volatilisation, denitrification, and leaching, or confounded by other external inputs of N unrelated to N fixation.
- A simple variation of N balance for quantifying N fixation is N difference. With this method, total N accumulated by N-fixing plants is compared with that of neighbouring non N-fixing plants, with the difference between the two assumed to be due to N fixation. The main assumption is that the N-fixing plants assimilate the same amount of soil mineral N as the neighbouring non N-fixing plants.
- Widespread use of 15N-based methodologies developed during the 1980s and beyond. The experimental protocols involved are: (i) labelling N in the atmosphere surrounding the N-fixing plants followed by measurement of incorporation of 15N by the plants, and (ii) growing the plants in 15N enriched soil or other growth medium and calculating the extent of dilution of 15N in the plants by atmospheric (fixed) 14N. A later variation of 15N isotope dilution utilised the natural 15N enrichment of soils, thereby avoiding the need to add 15N-enriched materials. In recent years, natural 15N abundance has gained prominence for work in both experimental plots and in farmers’ fields.

The N balance and N difference methods provide estimates of N fixation on an area basis, i.e. kg N/ha. The 15N method, on the other hand, provides estimates of the percentage of plant N derived from N fixation (% Ndfa). An amount of N fixed per unit area or unit of production can only be calculated when %Ndfa is combined with an estimate of organism biomass and total N content.

The key ingredients for accurately estimating N fixation per unit area (ha), individual field, catchment, region, country, continent or globe are reliable values for %Ndfa and total N accumulation of the N-fixing agent for a specific period of time (Herridge et al., 2008). Accurately estimating global N fixation for the symbioses of the forage and fodder legumes is challenging because statistics on the areas and productivity of these legumes are difficult to obtain. Smil (1999) assumed average annual N fixation rates of 200 kg N/ha for alfalfa, 150 kg N/ha for the clovers, 100 kg N/ha for other leguminous forages and 50 kg N/ha for legume–grass pastures.

Work in Australia and northern Europe shows that forage/fodder legumes have an average Ndfa value of about 70% and 25 kg N is fixed in the shoots for every Mg shoot biomass produced (Peoples and Baldock, 2001; Carlsson and Huss-Danell, 2003). Assuming 50% of forage legume N is below-ground (Peoples and Baldock, 2001), the overall average for N fixation by forage legumes becomes 50 kg N fixed/Mg shoot biomass. It has to be noted that there is considerable variation in the amount of fixed N per unit shoot biomass. Schils and Snijders (2002) reported values between 39 and 58 kg N/Mg, Elgersma and Hassink (1997) between 49 and 69 kg N/Mg, and Korsaeth and Eltun (2000) between 29 and 39 kg N/Mg.

3.2.1 Modeling

In clover, total N uptake is the sum of two processes: mineral N uptake and N2 fixation. Schwinning and Parsons (1996) assume that these processes do not occur in a fixed ratio. When soil mineral N content is low, clover obtains most of its N by fixation. As soil mineral N increases, clover obtains an increasing amount and proportion of N from soil nitrate. However, even at high mineral N, some N2 fixation (15% of total N uptake) may remain engaged. The model uses a parameter "e" that explores the efficiency of N uptake by fixation relative to mineral N uptake. When e = 1, the fixation rate is as efficient as the rate of mineral nitrate uptake and clover always achieves the maximal specific rate of total N uptake. Schwinning and Parsons estimate that e = 0.6.

Høgh-Jensen et al. (2004) developed an empirical model for quantification of symbiotic nitrogen fixation (SNF) in grass-clover mixtures. The model estimates SNF using dry matter yield as input and parameters for (i) N concentration in dry matter and the (ii) proportion of the N in the legume that is derived from the atmosphere. Further, the model includes fixed N not included in the estimate of SNF in aboveground herbage. Thus the model operates with parameters for (iii) the ratio of fixed N in below-ground plant tissue,
(iv) the ratio of fixed N transferred below-ground to the grass, (v) the ratio of fixed N transferred to the grass through the grazing animals, and (vi) the ratio of fixed N immobilised to the soil organic pool by rhizodeposition.

The model is constructed so that the part of fixed N2 in the shoot mass of a legume is corrected relatively for (i) the amounts of fixed N2 found below defoliation height at the end of the growing season or at maturity, (ii) the fixed N2 transferred to other species in the mixture via the soil or via grazing animals, and (iii) the fixed N2 immobilised in the soil in partly decomposed organic matter. These model components will be universal for grassland systems.

$$SNF = DM_{legume} \, x \, N_{\%} \, xP_{fix} \, x \, (1 + P_{rootstubble} + P_{transsoil} + P_{transanima} + P_{immobile})$$

where
- DM_{legume} = accumulated amount of legume shoot dry matter above normal defoliation height;
- N% = concentration of N in the dry matter of the legume (kg kg1);
- Pfix = fixed N2 as proportion of total N in the shoot dry matter of the legume;
- Prootþstubble = fixed N2 in the root and stubble as proportion of totally fixed shoot N at the end of the growing period;
- Ptrans soil = below-ground transfer of fixed legume N2 located in the grass in mixtures as proportion of total fixed shoot N at the end of the growing period;
- Ptrans animal = above-ground transfer (by grazing animals) of fixed legume N2 located in the grass in mixtures as proportion of total fixed shoot N at the end of the growing period;
- Pimmobile = fixed N2 immobilised in an organic soil pool at the end of the growing period as proportion of fixed shoot N at the end of the growing period.

Simple and empirical models based on experiments where 15N was used for determination of N2-fixation have been proposed earlier (Boller, 1988; Carlsson and Huss-Danell, 2003; Weißbach, 1995). Boller (1988) found 30 kg SNF per ton of harvested white clover dry matter using 15N methodology. This value is smaller than the value that can be derived using the model of Henning Høgh-Jensen, because the data of Boller (1988) originate from very fertile soils, thus Pfix is smaller, 70% in contrast to 95% in the present model. Weißbach (1995) found 37 kg SNF per ton of harvested white clover dry matter. Following a similar rationale, Carlsson and Huss-Danell (2003) suggested 31, 26 and 21 kg SNF per ton of harvested dry matter of white clover, red clover and lucerne, respectively. These estimates are based on the harvested biomass only and vary with N% and Pfix only. Weißbach (1995) proposed that the total input of SNF could be calculated by multiplying the SNF in the harvested leaf mass by a factor of 1.25, which results in a considerably smaller total input of SNF than by use of the present model .

Elgersma and Hassink (1997) used the total-N difference method and found an SNF of approximately 60 kg per ton of harvested white clover dry matter. The total-N difference method only gives valid estimates when the clover-grass mixture and grass in pure stand take up the same amount of N from the soil; this may however not always be the case (Høgh-Jensen and Kristensen, 1995; Høgh-Jensen and Schjoerring, 1997).

Based on a derivate of the total-N method, Watson and Goss (1997) proposed a model that is based on a linear relation between N2-fixation and dry matter yield excess in grass-clover swards compared with pure grass swards. For both grazed and cut swards, these relations would estimate approximately 70 kg SNF/ha per ton harvested clover biomass, which is close to the values predicted by the present model.

A review of nine widely-cited models (Liu et al., 2010) shows that most simulation models estimate the N fixation rate from a pre-defined potential N fixation rate, adjusted by the response functions of soil temperature, soil/plant water status, soil/plant N concentration, plant carbon (C) supply and crop growth stage.

Table 12 Simulation models that include legume BNF, and the factors considered in each model. fT , fW, fN, fC and fgro are the factor of soil temperature, soil/plant water, soil/plant nitrogen, plant carbon and plant growth stage, respectively.

Model	Factors					Simulated legume specie	Reference
	f_T	f_W	f_N	f_C	f_{gro}		
Sinclair Model*		✓				soybean	Sinclair (1986)
		✓			✓	soybean, cowpea, black gram	Sinclair et al. (1987)
EPIC		✓	✓		✓	soybean	Sharpley and Williams (1990); Bouniols et al. (1991); Cabelguenne et al. (1999)
Hurley Pasture Model	✓	✓	✓	✓		white clover	Thornley (1998); Thornley and Cannell (2000); Thornley (2001)
Schwinning Model*			✓	✓		field pea	Eckersten et al. (2006)
			✓			white clover	Schwinning and Parsons (1996); Schmid et al. (2001)
CROPGRO	✓	✓		✓	✓	soybean, peanut, drybean, velvet bean, faba bean, cowpea	Boote et al. (1998); Sau et al. (1999); Hartkamp et al. (2002); Boote et al. (2002, 2008)
SOILN	✓	✓	✓			white clover	Wu and McGechan (1999)
APSIM		✓	✓		✓	soybean, chickpea, peanut, mungbean, lucerne	Herridge et al. (2001); Robertson et al. (2002)
Soussana Model*			✓			white clover	Soussana et al. (2002)
STICS	✓	✓	✓		✓	field pea and other legumes	Brisson et al. (2009); Corre-Hellou et al. (2007, 2009)

4 Current methods in Member States

In different grassland surveys, member states collect a wide variety of relevant data (Table 13), either directly as yield, or indirectly through volume of grazed grass, volume of cut grass, number of cuts/harvests per year, management intensity, grazing status, grazing intensity, nitrogen input levels as fertiliser or manure, and proportion of clover or other N fixing plants. In most cases the collected data are yield related; only few collect data on legumes (biological nitrogen fixation).

Table 13 Collected data in grassland surveys per member state (results from questionnaire).

country	Yield (ton /ha)	Volume of grazed grass	Volume of cut grass	Number of cuts/harvests (times per year)	Management intensity (cleared, leveled, ploughed)	Grazing status (grazed, not grazed)	Grazing intensity (stocking density, daily duration)	Nitrogen input levels as fertiliser (kg N)	Manure input levels	% of clover or other N fixing Plants	Biological N fixation(in kg N / ha)
CH				v	v	v	v			v	
CZ	v										
DE	v		v								
DK	v										
EE		v	v					v	v		
EL											
ES											
FI	v			v		v		v		v	
FR	v			v		v	v	v	v		
HR	v	v	v								
HU	v	v	v			v		v	v		
IE	v			v		v		v	v		
IT											
LT	v	v	v			v					
LU	v										
LV	v	v			v						

ME											
NL			v	v							
NO	v		v	v	v						
PL											
PT	v	v	v	v		v					
RO	v										
RS	v		v								
SE						v		v			
SI	v			v			v				
TR											
UK						v				v	
Proportion (%)	56	22	33	26	7	30	7	22	15	7	0

4.1 Grassland production

The methods used to estimate grassland production are very heterogeneous (Table 14). Most members states use expert estimates, while destructive measurements are also mentioned frequently. Less frequently mentioned methods involve default values from literature, non-destructive measurements, calculations of a crop growth model and estimates using feed balance calculation. The specified options mentioned as ‘other’ methods are generally based on one of the standard categories.

Table 14 Methods used to estimate grassland yields in member states (results from questionnaire).

Member State	no	Yes, expert estimates	Yes, default values from literature	Yes, destructive measurements (harvests)	Yes, non-destructive measurements	Yes, use of remote sensing	Yes, calculations of a crop growth model	Yes, estimates using feed balance calculation	Yes, other (please specify)	specification
BE		1	1	1	1			1		
BE				1						
BE									1	NSI
CH									1	A mix between standard values from literature and expert estimates for each separate fodder year. We use all information over the fodder year (weather reports, news articles, information about crop situation, etc.) in order to adjust default values. Control values are given by

										fodder requirement from livestock taking also into account that stocks of forage are changing in a plausible way.
CH		1		1	1			1		
CH		1	1							
CH		1	1	1				1		
CZ		1		1						
CZ									1	statistical survey
DE		1							1	Ernte- und Betriebsberichterstattung (EBE) über Feldfrüchte und Grünland
DE		1		1	1		1	1		
ES		1	1	1					1	se utiliza el índice de Rosenzweig para extrapolar territorialmente los datos medidos
FI		1							1	Variety testing results and results from other experiments.
FR							1	1	1	agricultural annual statistics
FR							1			
HR		1								
HU									1	sample survey
IE		1		1	1					
IE									1	Grassland utilisation is estimated form National Farm Survey Data. Some Research plot data also available
IT		1								
LT									1	Data available from annual survey on on the area and the harvest on agricultural crops
LU		1							1	essais comparatifs variétés de graminées fourragères et légumineuses fourragères; essais sur les pratiques culturales en prairies et pâturages permanents: experimental fields for comparison of grass and leguminous fodder varieties; experimental fields on production methods in permanent grassland
LV									1	We have had a service called "Mowing service" having measured average data from each region of the country. But this service is not available any longer. Grass yield is measured individually now.
LV			1						1	As proportion of organic carbon stock in soil
NL								1		
NO				1						
PL		1							1	sample survey
PL		1								
PL		1	1	1			1			
PL		1	1	1			1			
PT		1								
PT		1	1							
SE									1	Standard value based on a calculation of a ratio compared to yield on temporary grasses. (1200 kg/hectare)
SI		1							1	reports of agricultural holdings which are enterprises and expert estimates for farmers (big share of all grassland

										area)
SI		1							1	reports of agricultural holding which are enterprises and expert estimates for farmers (big share of all grassland area)
SI		1								
SK				1						
SK				1						
UK	1								1	www.defra.gov.uk Fertiliser Manual (RB209) provides information for estimating crop requirements and using expected yield based on rainfall and soil type.

The temporal scale of grassland production estimates is mostly on an annual basis, but sometimes on smaller time windows: four-monthly, monthly or even weekly. It is remarkable that some member states mention a standard value for each year.

The spatial scale varies from National (NUTS0) to regional scale (NUTS 2/3), and further to farm or even field scale. Regional scales are mentioned most frequently.

4.2 Nutrient content in grasses

Most members states use derived values from literature or direct measurements in samples of harvested grass. The specified options mentioned as ‘other’ methods are generally based on one of the standard categories.

Table 15 Methods used to estimate nutrient contents in grass in member states (results from questionnaire).

	No	Yes, expert estimates	Yes, default values from literature	Yes, measurements	Yes, derived from measured protein contents of grass	Yes, other (please specify)	specification
BE		1	1	1	1		
BE			1				
BE							
CH			1				

CH				1			
CH							
CH				1	1		
CZ		1		1			
CZ			1				
DE				1	1		
DE				1			
ES		1	1		1		
FI				1	1	1	In reseach studies values are avaible for those particular materials included in the study.
FR		1					
FR							
HR							
HU			1				
IE				1	1		
IE						1	Some data is available from research experiments at some locations
IT						1	estimation based on ELBA model (Environmental Levelness Blant Agriculture) managed by Univerisity of Bologna
LT	1						
LU			1				
LV			1		1		
LV			1				
NL					1	1	Yes, derived from measured phosphorus contents of grass
NO			1	1			
PL	1						
PL	1						
PL		1	1	1			
PL			1	1			
PT		1					
PT		1	1				
SE						1	Source: STANK in mind
SI							
SI						1	Data on N and P content are available for farms which analyse their forages on voluntary basis in Slovenian labs.
SI						1	Data on N and P content are available for farms, which analyse their forages on voluntarly basis in Slovenian labs.
SK			1	1			
SK							
UK			1				

4.3 Biological nitrogen fixation

A significant proportion of member states do not collect data on biological nitrogen fixation in mixed swards (Table 16). Those that do, mostly rely on values retrieved from literature in combination with expert estimates. Measurements and models are not mentioned frequently.

Table 16 Methods used to estimate biological fixation in grasslands in member states (results from questionnaire).

	No	Yes, expert estimates	Yes, default values from literature	Yes, measurent	Yes, model calculations	Yes, other (please specify)	specification
BE		1	1	1			
BE			1				
BE						1	research report and papers
CH		1	1		1		
CH		1		1	1		
CH							
CH		1		1			
CZ	1						
CZ	1						
DE		1	1			1	Default values from literature for estimation of BNF of legumes and free-living organisms. Expert estimations of BNF by legumes in permanent pasture.
DE		1			1		
ES		1					
FI		1	1				
FR		1					
FR							
HR							
HU	1						
IE						1	calculated by difference
IE		1					
IT						1	Until 2002 OECD estimations
LT	1						
LU			1				
LV						1	We use a data from Swedish advisory tool- the program called Stank. Fixation intensity depends on a crop and its yield.
LV			1				

NL			1				
NO		1	1	1	1		
PL	1						
PL	1						
PL			1				
PL			1		1		
PT			1				
PT		1					
SE	1						
SI							
SI			1				
SI			1				
SK	1						
SK							
UK	1						

5 Guidelines

5.1 Currently available methods

The aim of this study is to review existing methodologies to estimate grassland production and biological fixation in grasslands. Grassland production and the associated nitrogen off take are an important part of nutrient balances. Therefore, knowledge of the underlying methods will help to better assess the uncertainty of nutrient balances. Furthermore, guidelines on appropriate methods will contribute to a more uniform and harmonized approach across EU member states.

Grasslands convert solar energy into plant biomass, which is utilized through grazing or cutting. Only a small fraction of light energy is finally ingested by livestock, or another end-user such as a digester. It seems obvious that from an agronomic point of view, only above ground biomass is considered as this is removed fraction. However, in between above ground biomass and net feed intake, there is still considerable room for different interpretations. The following definitions of grassland production may apply:

1. *Gross production*
   ...excluding harvest and grazing losses gives:
2. *Net production*
   ...excluding conservation and feeding losses gives:
3. *Net feed intake*

Thus, when assessing grassland production it is important to know whether gross grass production, net grass production or net feed intake was measured. Losses during harvest, grazing, conservation and feeding are variable, depending on the management system.

Table 17 Overview of grass production assessment methods

Method	Scale	Gross production	Net production	Net feed intake
Cutting and weighing	plot, field, farm	x	x	
Height and density measurement	plot, field	x		
Visual estimate	plot, field, farm	x	x	
Modeling	plot, field, farm, region	x	x	x
Remote sensing	region	x		
Feed balance	farm, region			x

In our review we distinguished six main categories for production estimates (Table 17):

1. Cutting and weighing is the most direct assessment method. It is carried out on experimental plots to determine gross production. It may also be carried out on farm fields to determine the harvested net yield of a complete field or farm.
2. Height and density measurements are carried out on experimental plots and complete fields. They are estimates of the standing crop (gross production).
3. Visual estimates may are usually carried out on a standing crop and thus give an estimate of gross production of plots and fields. However, visual estimates may also be performed on hay stacks or silage heaps in which case they are an estimate of net production at farm level.

4. Crop modeling is a powerful tool to estimate gross and net production over all possible scales. In combination with farm and livestock modeling it is also possible to estimate net feed intake.
5. Remote sensing in combination with crop modeling supplies estimates of gross production at larger scales.
6. The feed balance is in fact a simple model that estimates net feed intake, based on the feed requirements of livestock. It may be applied at farm or regional level.

In order to calculate nitrogen removals through grazed and harvested grass, the nitrogen content needs to be assessed. Methods used for measurement of nutrient contents in grassland comprise three main categories:

1. Sampling of herbage and subsequent laboratory analysis, mostly available from harvested hay or silage, but in specific cases also from fresh herbage.
2. Rapid non-destructive direct determination of nutrient content with near infrared reflectance spectrometry, or indirect determination through chlorophyll meters, which is an estimate for nitrogen content.
3. Remote sensing of reflectance spectra indicating chlorophyll content, which is an estimate for nitrogen content.

Nitrogen-fixing legumes are significant components of many agricultural systems. The amount of N fixed by clover is difficult to estimate, because both the estimate of the average share of clover in grassland in a region and the amount of N fixed by clover are uncertain. The major methods used to determine BNF are:

1. Direct measurement of legume BNF in the field, usually only executed at experimental plot level.
2. Modeling of legume BNF is applicable from plot to regional scale.

Currently, Member States collect a wide variety of yield data, either directly as yield, or indirectly through volume of grazed grass, volume of cut grass, number of cuts/harvests per year, management intensity, grazing status, grazing intensity, nitrogen input levels as fertiliser or manure, and proportion of clover or other N fixing plants.

The methods used to estimate grassland production are very heterogeneous. Most members states use expert estimates, while destructive measurements are also mentioned frequently. Less frequently mentioned methods involve default values from literature, non-destructive measurements, calculations of a crop growth model and estimates using feed balance calculation.

With respect to nutrient contents, members states mainly use derived values from literature or direct measurements in samples of harvested grass.

Data on biological nitrogen fixation are usually not collected. Those member states that do, mostly rely on values retrieved from literature in combination with expert estimates. Measurements and models are not mentioned frequently.

5.2 Proposed tiered approach

Taking into account the large variation in available methods and the large variation in currently applied methods, the challenge is to develop a harmonized framework for grassland production, nutrient content and biological nitrogen fixation. The variety in methods described for the three different parameters, decreased in the order yield, nutrient content and biological nitrogen fixation. Despite these large differences in underlying methods we suggest a tiered approach for each of the three parameters.

The three proposed levels are:

1) Fixed estimate
2) Modeled, including feed balances
3) Direct measurements

These levels do not represent one single method per tier, but a cluster of methods. This allows freedom of methodology as long as the methodology is clearly described. In fact, nearly all methods described in this report may be considered. Only remote sensing currently seems a step to far. Although the ability to model production with remote sensing based data has increased significantly in recent years, a valid method across all regions has not yet evolved.

In theory, each of the three methods can be applied at different spatial and temporal scales, but it makes sense that the spatial and temporal resolution increase from tier one to tiers two and three. For each of the three approaches, it is evident that there has to be a clear description available which contains definitions, assumptions, calculation methods, used models and measurement techniques, as well as upscaling methods from plot, field, farm, region to national estimates and from individual harvests to annual yields. Table 18 shows, for each tier, an overview of the sources, temporal and spatial scales, risks and uncertainties, and relative costs.

Table 18 Framework for three tiered approach.

	Fixed estimate	Models	Measurements
Sources	• Literature • Experts	• Calibrated and validated model • Meteorological data • Farm management data • Statistical farm data • Feed requirements • Data on imported feed • Data on legume contents in swards	• Network of experimental plots • Network of commercial (pilot) farms
Temporal scale	• Annual	• Seasonal • Annual	• Seasonal • Annual
Spatial scale	• Regional • National	• Regional • National	• Regional • National
Uncertainties and risks	• Expert bias • Incomplete spatial coverage of data	• Availability of data for calibration and validation • Feed balances require many additional data on livestock and external feed inputs and quality	• Overestimation of actual yields • Availability of representative monitoring network
Relative costs	• Low	• Medium	• High

Fixed estimates are those values that are derived from literature research in combination with expert opinions. Sources are preferably peer reviewed papers, but data from other sources may be used as well. Often data availability is limited with white spots for certain areas or periods. Regional and national grassland experts are a valuable resource for completing these missing data. Data availability will decrease in the order yield > nutrient content > fixation, but in all cases the framework of the approach is similar.

Modeled estimates comprise a wide range of empirical or mechanistic approaches of estimating yields, nutrient content or biological fixation, with varying complexity. Models are preferably published and peer reviewed and calibrated and validated on local conditions. Models need good quality data on weather, farm management, nutrient inputs, botanical composition. Again in this category, models for yield estimates are developed abundantly, compared to models for nitrogen fixation. With respect to yield estimates, the use of feed balances has been applied in several countries and may serve as a template for other member states. Feed balances require additional data on livestock feed requirements and amounts and quality of imported feed. Less experience is available for nitrogen fixation. Whichever modeled approach is chosen, the most important underlying factors, proportion of legumes in the sward and applied nitrogen, should be considered.

Measured estimates are those values derived from *in situ* measurements of yields, nutrient contents of nitrogen fixation. Although the direct measurement is in theory the best proxy, the methods has similar pitfalls as the lower tier methods with respect to upscaling from a local site at a specific time to higher spatial and temporal scales. Furthermore it has to be clear that on experimental sites potential yields are measured such as in the grassland network used in the 1980's (Corrall, 1988; Peeters & Kopec, 1996). Potential yields are significantly higher than those obtained under commercial farming conditions. Therefore, measurement networks should preferably be located at commercial farms, on plots used for grazing as well.

5.3 Required data collection

The removal of nitrogen and phosphorus with harvested and grazed grasslands is required to calculate the gross nitrogen and phosphorus balances. A tiered approach to estimate grassland production is recommended, expressed in dry matter yield, nitrogen yield, and phosphorus yield.

In the Tier 1 method, estimates of grassland yields and nutrient contents should be made on a preferably NUTS II level, or for smaller member states at national level, and annual basis. This has to be done for the grasslands categories that are relevant for nutrient balances. Table 19 shows the proposed table that has to be filled for a Tier 1 method.

Table 19 Proposal for a table to be used in a Tier 1 approach for estimates of dry matter yields, N and P contents of grassland, for different hypothetical grassland classes and regions in EU.

	Region/member state					
Grassland category	1	2	3	4	5	etc.
A						
B						
C						
D						
etc.						

The N and P contents in dry matter, which are needed to calculate the total N and P removal by the harvested crops, should also be estimated for all relevant grassland types. If data are available, estimates nutrient contents on a national of regional level can be used. It is recommended that the required estimates of dry matter yield and nutrient content are derived by one group of experts, using a combination of data sources The advantage of deriving yields estimates by one expert group instead of estimates by country experts is that a uniform approach is used that guarantees that the yields are estimated with the same approach. If the proposed estimates of grasslands and nutrient contents are available, the calculation of gross nutrient balances on NUTS II level will be significantly improved and harmonized over the European Union, compared to the current estimates.

The data required for the Tier 2 (modelling including feed balances) and Tier 3 (measurements) methods strongly depend on the approach that will be used. No general recommendations can be made for data collection using Tier 2 and 3.

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Appendix 1 References to methods

Grassland Yield

BE	http://statbel.fgov.be/nl/modules/publications/statistiques/economie/downloads/production_des_cultures_agricoles.jsp
CH	The production of forage plants is estimated in a indirect way. Swiss farmer's Union SFU calculates the production of rough forage with their crop yield survey, the agricultural area and livestock survey of the federal statistical office, the period of grazing, etc. The stock variations and the distribution amongst the used channels are estimated by SFU with the help of the fodder balance sheet. see also : http://www.bfs.admin.ch/bfs/portal/en/index/themen/07/22/publ.html?publicationID=3619 (page 42 and 43)
CZ	www.czso.cz
DE	Methodologies applied to estimate the yields are published in quality report "Ernte- und Betriebsberichterstattung (EBE): Feldfrüchte und Grünland, Anlage 4" by Destatis. https://www.destatis.de/DE/Publikationen/Qualitaetsberichte/LandForstwirtschaft/ErnteEBE.pdf?__blob=publicationFile
DE	www.gruenland-online.de
ES	"Propuesta para la modificación de los Balances de N y P en zonas de pastoreo exclusivo o permanente, barbechos, rastrojeras y cultivos forrajeros pastoreados" dentro de los trabajos de los Balances de N y P en la Agricultura Española, del MAGRAMA. En redacción.
FI	For variety testing annual reports are available in the internet at: http://www.mtt.fi/mttraportti/pdf/mttraportti75.pdf Ministry of Agriculture and Forestry with TIKE provides annual yield estimates in their statistics: http://www.maataloustilastot.fi/satotilasto
FR	see agreste website data on grassland crop model are confidential
IE	CORRAL, A. J. and FENLON, J. S. (1978). A comparative method for describing the seasonal distribution of production from grasses. Journal of Agricultural Science, 91, 61-67. http://www.agresearch.teagasc.ie/moorepark/Publications/pdfs/OpenDay2011GrassCalculator.pdf http://www.agresearch.teagasc.ie/moorepark/Publications/pdfs/Open%20Day%20Moorepark%202009%20Grazing%20Manual.pdf
LT	Survey methodology: http://osp.stat.gov.lt/documents/10180/550594/Statistical_survey_of_agricultural.pdf/91607f58-249e-4473-a1c6-668ab467cfee
LV	There are no Internet based sources for methodologies applied to estimate the yields. The methodology we use is: manually cut the grass of one square meter in several places of the field, weight it all and multiply the result to get the total weight of one hectare. Example: grass from 4 square meters has been taken and the total weight is 3kg, we multiply 3 with 2500 to get yield in kilograms from one ha (10'000 sq m) and it is 7'500kg per ha per one cut. We repeat it the same number of times as the number of mowing times is getting total grass yield per year. 25 tons of grass is a satisfactory result.
LV	IPCC GPG LULUCF (2003) default factors for grassland yields, mostly as an input data to estimate effect of grassland fires.
NL	see chapter 3.2.1. from the publication: http://www.cbs.nl/NR/rdonlyres/424DD391-C1CB-4955-942F-D6C75BEBF630/0/2012c173pub.pdf
NO	http://www.ssb.no/en/jord-skog-jakt-og-fiskeri/statistikker/jordbruksavling/aar/2013-02-04?fane=om#content
PL	Only following information is available: "For converting green fodder into hay it was assumed that 5 dt of green fodder = 1 dt of hay".
PL	http://www.stat.gov.pl/cps/rde/xbcr/gus/rs_rocznik_rolnictwa_2012.pdf
PL	www.imuz.edu.pl data of Central Statistical Office http://www.stat.gov.pl/gus/5840_11215_ENG_HTML.htm
PL	www.imuz.edu.pl date of Central Statistical Office: www.stat.gov.pl/gus/5840_11215_ENG_HTML.htm
PT	Samples from field trials
SI	http://www.stat.si/doc/metod_pojasnila/15-024-ME.pdf
SI	http://www.stat.si/doc/metod_pojasnila/15-024-ME.pdf

SI	http://www.stat.si/letopis/2012/MP/16-12.pdf
SK	T´here is published information on data for yield of agricutlural crops in Slovakia every year, e.g. "Definitive data for yield of agricultural crops and vegetables in the Slovak Republic for the 2012 year - Slovak version. (http://portal.statistics.sk/files/Sekcie/sek_500/polnohospodarstvo/publikacie-stiahnutie/definitivne-udaje-uroda/definitivne-udaje-uroda-2012.pdf)
SK	Definitive data for yield of agricultural crops and vegetables in the Slovak republic, http://portal.statistics.sk/files/Sekcie/sek_500/polnohospodarstvo/publikacie-stiahnutie/definitivne-udaje-uroda/definitivne-udaje-uroda-2012.pdf
UK	www.defra.gov.uk Fertiliser Manual RB209 provides information for estimating crop requirements and using expected yield based on rainfall and soil type.

Nutrient content

CH	Data are part of the report: „Grundlagen für die Düngung im Acker- und Futterbau“ which is published and regularly updated by our research institute Agroscope: http://www.agroscope.admin.ch/systemes-cultures/03624/index.html?lang=de
CH	chemical analysis
CH	http://www.agroscope.admin.ch/futtermitteldatenbank/index.html?lang=de
CZ	http://www.vurv.cz/sites/File/Publications/ISBN978-80-87011-61-4.pdf
DE	National data on nitrogen and phosphorus contents in grass are published in the German fertilization ordinance (Düngeverordnung, DüV) based on measurements and field trials done by the chambers of agriculture of every federal state.
DE	ask here LTZ Karlsruhe Augustenberg (Dr. Werner Ueblehoer) werner.uebelhoer@ltz.bwl.de
ES	"Propuesta para la modificación de los Balances de N y P en zonas de pastoreo exclusivo o permanente, barbechos, rastrojeras y cultivos forrajeros pastoreados" dentro de los trabajos de los Balances de N y P en la Agricultura Española, del MAGRAMA. En redacción.
FI	Probably most comprehensive data on nitrogen content could be retrieved from dairy company Valio's NIRS based feed value service. Thousands (tens of thousands) of analysis area carried out every year and samples are from farms. Individual research studies results include values for nitrogen and phosphorous content in those experiments.
FR	exportation coefficients http://www.chambres-agriculture-picardie.fr/fileadmin/documents/Environnement/MAE/ref_corpen_export_culture_NPK.pdf
HU	N, P contents are based on the Hungarian Nitrate Regulation published in 2009.
LV	The content of nitrogen and phosphorus is estimated in certified laboratories.
NL	see chapter 3.2.1. from the publication: http://www.cbs.nl/NR/rdonlyres/424DD391-C1CB-4955-942F-D6C75BEBF630/0/2012c173pub.pdf
NO	http://www.umb.no/iha/artikkel/fortabellen
PL	http://www.iung.pulawy.pl/index.php?option=com_content&view=article&id=87:glach&catid=39:organizacjaiung&Itemid=109
PL	http://www.iung.pulawy.pl/index.php?option=com_content&view=article&id=87:glach&catid=39:organizacjaiung&Itemid=109
PT	Dry matter yield and N and P content in dried material.
SE	Stank in mind: http://www.svensktsigill.se/PageFiles/761/B11-%20Manual%20och%20information%20f%c3%b6r%20att%20ber%c3%a4kna%20v%c3%a4xtn%c3%a4ringsbalans%202011.pdf
SI	Nitrogen http.//www.govedo.si/files7janezj2/ZED_2011/kakovost_voluminozne_krme_in_prireja_mleka_v_sloveniji.pdf Phosphorus http.//www.govedo.si/files7janezj2/ZED_2011/gospodarjenje_s_fosforjem_in_kalijem_na_govedorejskih

	_kmetijah.pdf
SI	Nitrogen http://www.govedo.si/files/janezj2/ZED_2011/kakovost_voluminozne_krme_in_prireja_mleka_v_sloveniji.pdf Phosphorus http://www.govedo.si/files/janezj2/ZED_2011/gospodarjenje_s_fosforjem_in_kalijem_na_govedorejskih_kmetijah.pdf
SK	Decree of the Ministry Agriculture of the Slovak Republic No. 2145/2004-100 on requirements for testing and evaluation requirements and further biological validation of feed. Available in Slovak language on http://www.mpsr.sk/index.php?start&navID=126&year=2004
UK	www.defra.gov.uk RB209 Fertiliser Manual

Nitrogen fixation

BE	see elisabeth.jerome@ulg.ac.be Projet D31-1235 Etablissement du bilan de carbone d'une exploitation agricole wallonne pratiquant le système allaitant : effets du climat et de la gestion du pâturage Rapport de synthèse Janvier 2010 – Décembre 2011
CH	The model is based on surfaces of 7 types of grasslands (corresponding to the categories of our national FSS see above) each being subdivided in 6 "altitude" (production zone) classes. Production and share of Trifolium sp. are estimate with standard values (defined by experts) for each category. The share of fixed N by weight of Trifolium sp. is from literature. This model gives a rough estimates of the biological fixation in grassland.
DE	H. Kolbe, Comparison of methods for calculation of legume N2 fixation for use in practical agriculture [Vergleich von Methoden zur Berechnung der biologischen N2-Fixierung von Leguminosen zum Einsatz in der landwirtschaftlichen Praxis], Pflanzenbauwissenschaften, 13 (1). S. 23–36, 2009, ISSN 1431-8857.
DE	cited in: Elsaesser, M., 1999: Auswirkungen reduzierter Stickstoffdüngung auf Erträge, Futterwert und Botanische Zusammensetzung von Dauergrünland sowie Nährstoffverhältnisse im Boden. Habilitationsschrift, Universität Hohenheim, Wissenschaftsverlag Dr. Fleck, Gießen.
FI	One recent report which is based on literature study: http://jukuri.mtt.fi/handle/10024/480767
LV	No, we do not have it. No or not representable research is done in this field.
LV	http://www.ldf.lv/upload_file/28934/LDF-057-072-rusina.pdf http://llufb.llu.lv/proceedings/n17/3/llu-proceedings-17-3.pdf http://www.riski.lv/upload_file/Vide/Raksts.pdf
NL	See link at question 9, chapter 3.3, 4.4 and 5.4
PL	http://aciar.gov.au/publication/MN136 Doré T, Makowski D, Malézieux et al (2011) Facing up to the paradigm of ecological intensification in agronomy: Revisiting methods, concepts and knowledge. Europ J Agron 34(4): 197–210 Ledgard SF, Steele KW (1992) Biological nitrogen fixation in mixed legume/grass pastures. Plant and Soil 141: 137–153 Ta TC, Faris MA (1987) Species variation in the fixation and transfer of nitrogen from legumes to associated grasses. Plant and Soil 98: 265–274
PL	Doré T, Makowski D, Malézieux et al (2011) Facing up to the paradigm of ecological intensification in agronomy: Revisiting methods, concepts and knowledge. Europ J Agron 34(4): 197–210 Ledgard SF, Steele KW (1992) Biological nitrogen fixation in mixed legume/grass pastures. Plant and Soil 141: 137–153 Ta TC, Faris MA (1987) Species variation in the fixation and transfer of nitrogen from legumes to associated grasses. Plant and Soil 98: 265–274
PT	Manual Handbook for Gross Nutrient Balance (OECD/Eurostat).
PT	Using N15, or using the difference method (comparing N content in legume and non-legume species)
SE	Not for grassland