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Papers presented at the International Farewell Symposium

"Grassland Science in Perspective"

and Farewell address at the occasion of the official retirement of
Professor Leendert 't Mannetje

on June 20, 1996,
in the Aula of the Wageningen Agricultural University,
The Netherlands

Elgersma, A, Struik, P.C. and Maesen, L.J.G. van der (Editors)

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L.J.G. van der Maesen

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Preface

This issue of the Wageningen Agricultural University Papers is a tribute to Professor Leendert 't Mannetje at the occasion of his official retirement from the Wageningen Agricultural University. It contains the extended manuscripts of the papers presented at the International Farewell Symposium "Grassland Science in Perspective", organized by representatives of the Department of Agronomy and held in Wageningen, on June 20 1996, as well as the full text of the farewell address of Professor 't Mannetje, entitled "Grassland Science; Does it exist?", given on the same day.

This collection of papers highlights the outstanding contribution of Professor 't Mannetje to both science and education in the different aspects of the discipline "grassland and forage science". Among these aspects are: the development of the dry weight rank method that allows non-destructive analysis of the botanical composition of a pasture; the taxonomy of the genus *Stylosanthes*; the use of leguminous species in tropical and temperate grasslands; the interactions between the grazing animal and the grassland vegetation; the nitrogen husbandry of grasslands; the quality of roughages; and biodiversity aspects of grassland vegetations.

Grassland scientists and students world-wide have profited from Professor 't Mannetje's scientific input, have enjoyed his presentations and discussions, have benefited from his knowledge and communication skills, and have experienced his friendship, his forthrightness and his open-mindedness.

We hope that the readers agree with us that these proceedings put his contribution to grassland science in the right perspective and will serve to keep our recognition and our remembrance vivid.

The Department of Agronomy will continue to serve grassland science to the best of its abilities.

The Editors

A. Elgersma
P.C. Struik
L.J.G. van der Maesen

Simulation of the dry weight rank method

J.H. Neuteboom

*Department of Agronomy, Wageningen Agricultural University,
Wageningen, The Netherlands*

Abstract

With the Dry Weight Rank (DWR) method of 't Mannetje and Haydock (1963) for the botanical analysis of pastures, the dry weight proportions of species are estimated from their first, second and third ranks in single quadrats on the basis of dry weight. The method is tested with computer simulation.

First element in the simulation is a sampling program. The output shows that an important condition for the proper functioning of DWR is that species grow patchwise. However, only a certain amount of patchiness is required and probably in most vegetations this condition is fulfilled. This role of patches explains why quadrat size is relatively unimportant in DWR and could remove the still existing uncertainty with the method about the role of horizontal vegetation structure. Combined with the Jones and Hargreaves' (1979) yield correction, the method will probably work well in most vegetations. However, care should be taken in applying the method for estimating species composition in recently sown grasslands, where species can occur with more or less random plant distributions.

Introduction

The Dry Weight Rank (DWR) method for the analysis of botanical composition of pastures was developed in Australia by 't Mannetje and Haydock (1963) as a means to estimate quickly and accurately the species composition of grassland swards on a dry weight basis. The only methods available earlier were either hand-sorting of cut samples (very labour intensive) or estimates by eye (not reliable).

The DWR method was based on the 'Rank method' of De Vries (1933) (De Vries and De Boer, 1959), which resulted in 'relative importance percentages' (rI%). These were obtained by estimating in terms of bulk the species occupying the first three ranks in each of a number of quadrats. The total number of times a species received a rank was expressed as a percentage of the total number of these ranks of all species. When compared to dry weight percentages (DW%) the same order of species was obtained, but rI% was not closely related to DW%. Later in a lecture, De Vries mentioned that "the modern way of calculation is to allocate 3 points to a first place, 2 to a second and 1 to a third place". However, he did not indicate how these results related to DW%. The DWR method modified the rank method in essential ways; firstly, the ranking of species is not in bulk, but on the basis of dry weight proportions in a quadrat and secondly a set of empirical multipliers was determined for weighing the ranks in order to calculate the botanical composition in terms of DW%.

The empirical coefficients were derived from sets of data of which the exact DW% of all species was known from quadrat data providing the dry weights of each species. The multipliers derived by 't Mannetje and Haydock (1963) were 0.702, 0.211 and 0.087.

Rank proportions are weighed and added according to

$$DW_A\% = 0.702\ (A1\%) + 0.211\ (A2\%) + 0.087\ (A3\%)$$

(*species A; A1%, A2%* and *A3%* are the proportions of first, second and third ranks, respectively; $DW_A\%$ is dry weight proportion).

The coefficients were modified by Jones and Hargreaves (1979) to 0.714, 0.247 and 0.039 from further sets of data, although these do not lead to substantially different results.

The DWR method is fast, because there is no need for cutting and hand-separating samples. The observer has only to decide whether there is a greater dry weight of one species than of another. However, the method requires experienced observers and training beforehand is essential. Difficulties may arise because of large differences in dry matter concentrations of species and because some species are more prominent to the eye than others and therefore tend to be overestimated.

One of the restrictions of the method is that the calculated dry weight proportions can never exceed the value of 70.2%. This can be overcome by allocating first and second ranks to any species which occupies at least 75% of the total dry matter of a quadrat (Jones and Hargreaves, 1979). Another problem arises when there is a constant relationship between species dominance and quadrat yield. If a particular species always takes first rank in high yielding quadrats and another one takes first rank in low yielding ones, the former will be underestimated and the latter overestimated.

This can be solved by applying yield corrections, e.g. by simultaneously using the Comparative Yield Method of Haydock and Shaw (1975).

't Mannetje and Haydock (1963) did not find an effect of quadrat size on the results of DWR and claimed that the method is universally applicable regardless of the type of vegetation, because it is based on dry weights. On the other hand, rank proportions are frequency proportions, while it is known from presence frequency estimates of species in sampling quadrats (Greig-Smith, 1983) that these are strongly influenced by pattern. Van Dyne *et al.* (1975) questioned whether the DWR method is really independent of vegetation structure.

The possible role of quadrat size and pattern was investigated by means of a model approach by Sandland *et al.* (1982). They studied the role of quadrat size by varying the total plant numbers in quadrats in samplings of fictional mixtures with Poisson-distributed species (all species with Poisson-distributed plants), and concluded that samplings with large quadrats theoretically lead to heavy overestimations of high dry weight proportions. Clumping of species, studied by using special statistical functions, in principle seemed to improve the DWR estimations. However, the authors also stated that further quantifying these effects in a purely statistical way would be very difficult.

In this paper the role of quadrat size and clumping are analysed by means of a sampling program developed for personal computers. In the same way as in the simulations by Sandland *et al.* (1982), the effect of quadrat size was analysed for randomly distributed species by varying the total plant numbers per quadrat. However, pattern was analysed in a simpler way: by alloting species to randomly distributed circular patches.

Theory

Sampling program and assumptions

The sampling program for PC will be discussed in detail by Neuteboom *et al.* (in prep.). Basis of the program is the sampling of square plots in a fictional vegetation with Poisson-distributed species or with species in patches, with a circular sampling quadrat. 'Species in patches' means that species are allocated to circular patches occurring in a given density. The condition is that within one patch, only one species can occur. Plants and patches are assigned randomly selected x- and y-coordinates, for calculating their position with respect to the sampling quadrat.

All species are assumed to have circular plants of the same size, the same yield per plant and the same dry matter concentration. This means that their plant number proportions are identical to their dry weight proportions, and thus, that given the total plant density, their plant numbers can be calculated from their dry weight proportions. These dry weight proportions are calulated from a geometric series relationship after Scott (1986). Plants of species are recorded as present in the sampling quadrat when they fall with their centre point within the quadrat or are only touched by the quadrat.

The effect of quadrat size is investigated for randomly distributed species by varying the total plant numbers per quadrat. Patch densities for species in patches are calculated from the summed relative spaces the 'patch species' occupy in the whole mixture, and these also can be derived from their dry weight proportions. As patches can overlap, it has been decided that in the overlap zones of patches always the species assigned to a higher patch number counts. Screen pictures of randomly distributed species and of species in patches are given in Figure 1.

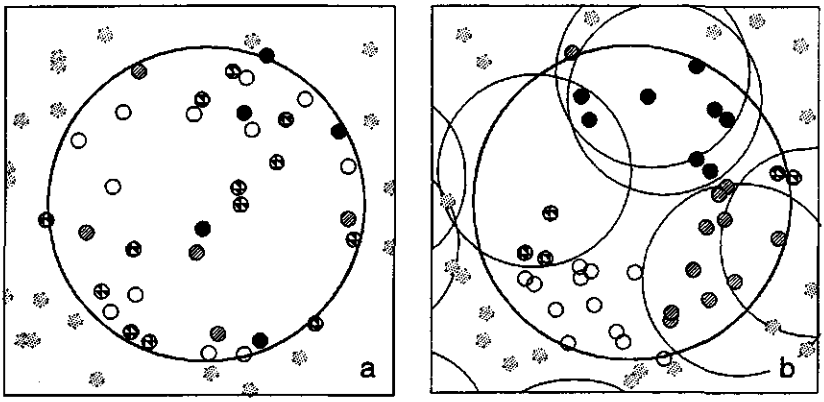

Figure 1. Two samplings pictured on PC screen. a) 4 species (○, ◍, ●, ⊗) randomly distributed; b) the same 4 species, of which 3 (◍, ●, ⊗) in circular patches; one species per patch. Only plants hit by the circular sampling quadrat (the large, bold quadrat in the centre of the squares) were assigned a species name. Plants not hit by the quadrat are represented by grey spots.

From the plant numbers per species recorded as present in the quadrat, the rank of each species is determined. In cases of shared first and second, or second and third ranks, the sharing species get assigned *1/2*, and in cases of shared first, second and third ranks, *1/3* of the sum of the shared ranks. After sampling of the last square, the ranks of the species are summed in order to calculate their total fractions or proportions of first, second and third ranks.

The rank proportions are used in the DWR equation for estimating the dry weight proportions. These estimated dry weight proportions can be compared with the real whole mixture dry weight proportions of the species calculated from their plant numbers. Calculated are also the real dry weight proportions at which species received first, second and third ranks in single quadrats. These dry weight proportions can be compared with the coefficients of DWR.

Calculation of mass proportions of species from the geometric series
According to the geometric series, the proportional contribution (*PR*) of a species (S_x) can be calculated from its rank (R_{Sx}) in mass and a parameter *k* (May, 1975; Magurran, 1983):

$$PR_{Sx} = k\,(\,1\,-\,k\,)\ \exp(\,R_{Sx}\,-\,1)$$

Parameter *k* gives the fractional reduction in proportion between the successively ranked species. From the *k*-values dry weight proportions ($DW\%_{Sx} = PR_{Sx} * 100$) are calculated in principle for an infinite number of species; however, in the sampling program the maximum number of species is set at 9. Figure 2 shows for $k = 0.5$ the calculated dry weight proportions of successive species and their cumulative dry weight proportions.

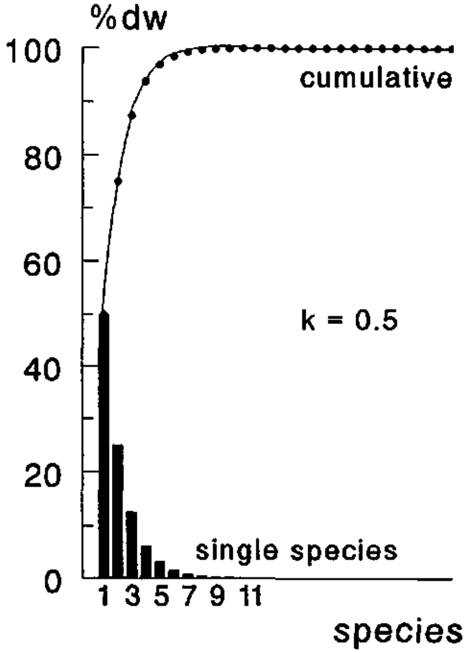

Figure 2. Dry weight proportions of species as calculated from the geometric series for k = 0.5.

Scott (1986) concluded from observations in pastures at Parkhouse, Rothamsted, that the geometric series fitted the data of dry weight proportions of species very well, which suggests that for modelling purposes, the series can simulate more or less realistic botanical compositions.

Scale of simulation
Where possible, data used in the simulated samplings are on field scale. All simulations were executed with a plant density of 3 plants/dm^2. This density originates from plant density experiments of Kreuz (1969) and van Loo (1991) with *Lolium perenne* (Neuteboom *et al.*, 1992), and could be considered as the equilibrium density of a *Lolium* sward 3 years after sowing. The patch sizes used in the simulations for species in patches are in between the sizes found for dung and urine patches in the literature. Richards and Wolton (1976) calculated a mean dung patch size of *5* dm^2 and a mean size of urine patches of *49* dm^2. Dung and urine patches and also mole patches are often the origin of the clumped occurrence of species in pastures. The maximum patch size of *13.8* dm^2 used in the simulated samplings was large enough to demonstrate the effect of patchwise distributed species in DWR sampling.

Results and discussion

Theoretical samplings were executed for different cases always with series of 19 mixtures containing 3 or 6 species in varying dry weight proportions. First, samplings were executed with different quadrat sizes (0.18, 1.67 and 8.79 dm^2) in series of mixtures with Poisson-distributed species. Then, samplings with the large quadrat size of 8.79 dm^2, of series of mixtures with species in patches; patches of 5.3 dm^2 (patch radius 1.3 dm), 9.1 dm^2 (patch radius 1.7 dm) and 13.8 dm^2 (patch radius 2.1 dm), respectively. In the 3 sampling cases of species in patches, one species was always in the background area, while the other species were in patches.

Only the results from the samplings with the large quadrat of 8.79 dm^2 are discussed, because these are the most interesting. The samplings with that quadrat in the mixtures with Poisson-distributed species, and in the mixtures with species in patches of 5.3 dm^2, 9.1 dm^2 and 13.8 dm^2, respectively, are summarized in Figure 3. The figure shows the DWR-estimated and real whole mixture dry weight proportions for each of the sampling cases. For 3 cases (species Poisson-distributed, and species in patches of 5.3 dm^2 or 9.1 dm^2) the relation between both parameters is represented by a smooth line, for one case (species in patches of 13.8 dm^2) individual points have been plotted (each point stands for one species; 6 species * 19 mixtures = 114 points). The dry weight proportions were calculated from DWR on the basis of numbers of

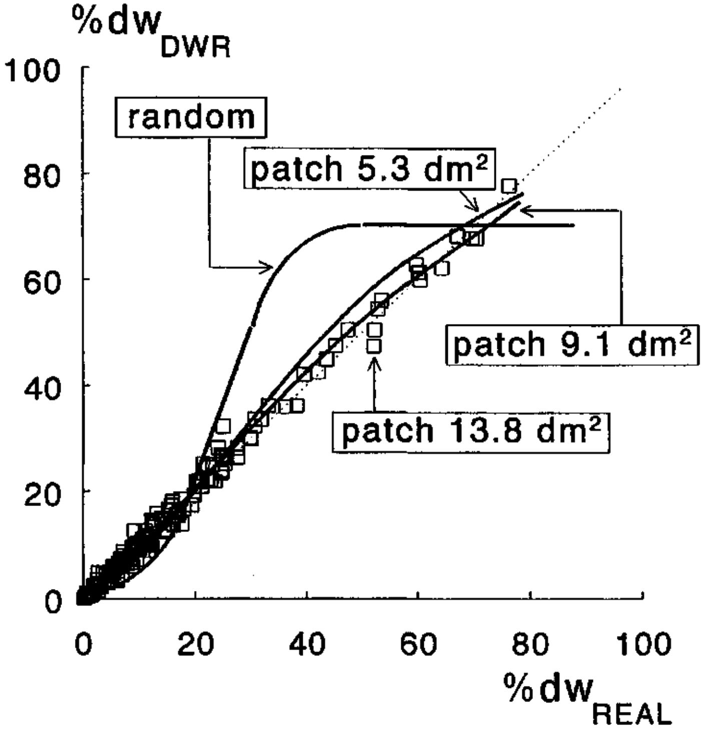

Figure 3. Output from samplings of series of always 19 mixtures containing 6 species with a total plant density of 3 plants/dm². Samplings with a quadrat of 8.79 dm², 80 samples per mixture. There are 4 cases: mixtures with randomly distributed plants (random) and mixtures with species in patches of 5.3 dm², 9.1 dm² or 13.8 dm². Given are for each of the cases the real whole mixture dry weight proportions ($\%dw_{REAL}$) and the dry weight proportions estimated from DWR ($\%dw_{DWR}$). For 3 cases (species random, and species in patches of 5.3 dm² and 9.1 dm²) the relation between both parameters is represented by a smooth line; for one case (species in patches of 13.8 dm²) the single points have been plotted. Each point stands for one species in one mixture, the total number of points is 19 mixtures * 6 species = 114. The DWR estimated dry weight proportions were corrected for missing ranks.

ranks instead of rank proportions, which solves the problem of missing ranks ('t Mannetje and Haydock, 1963).

Like Sandland *et al.* (1982), I found that samplings of mixtures with Poisson-distributed species with a large sampling quadrat lead to strong overestimations in the range of high dry weight proportions (Figure 3). Species in patches removed these overestimations, and surprisingly, very acceptable DWR estimations were already obtained with the relatively small patch size of 5.3 dm². Larger patch sizes could hardly further improve the DWR-estimations.

Since this is not the place to explain everything in detail (see Neuteboom *et al.*, in prep.) I can only focus on some main points. The main reason of the strong overestimations in the case of Poisson-distributed species is the dominant occupation of first ranks by the dominant species, already in a range of only moderately high dry weight proportions (the mid range of dry weight proportions in Figure 3; see also Figure 4a), and the high first coefficient of DWR.

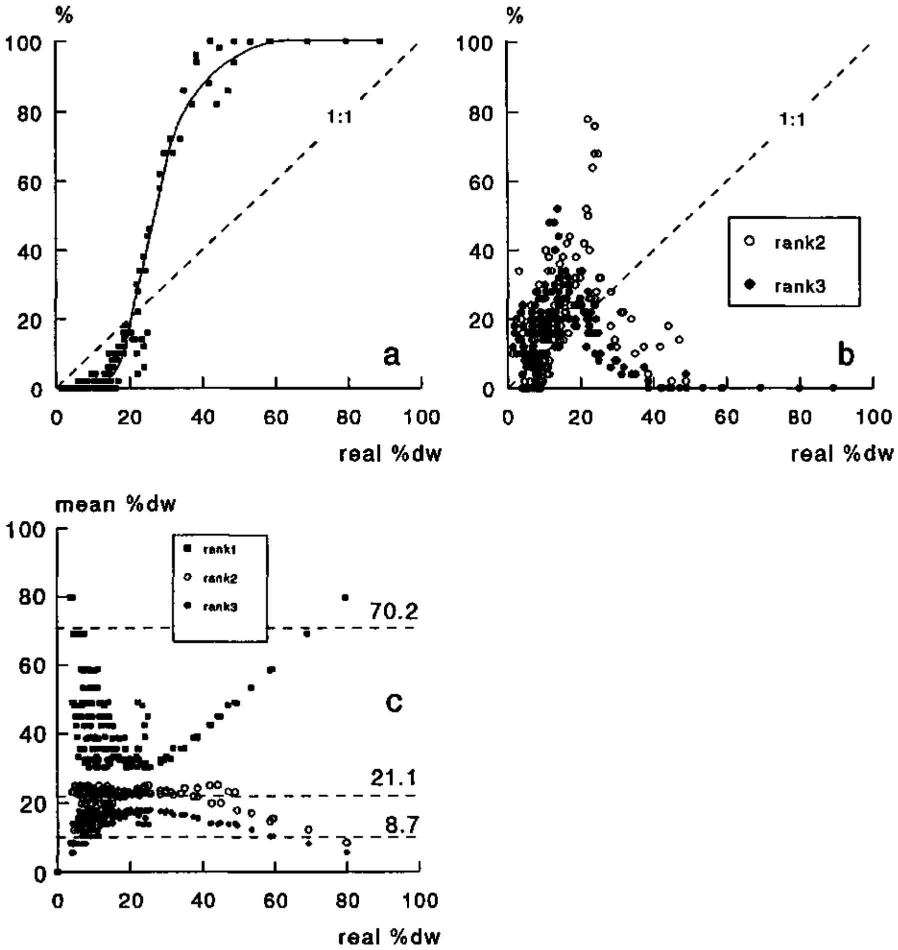

Figure 4. Percentages first ranks (a) and percentages second and third ranks (b) plotted against the real whole mixture dry weight proportions of the species in the mixtures with randomly distributed species. In (c) the mean percentages dry weight species received at first, second and third ranks in single quadrats are plotted against their real whole mixture dry weight proportions. Each point stands for one species in one mixture, the total number of points is 19 mixtures * 6 species = 114.

The reason of the dominant occupation of first ranks is the relatively uniform plant distribution of Poisson-distributed species. In the extreme case, large quadrats each reflect the species composition of the whole mixture. The first coefficient highly overestimates the real dry weight proportions species receive at first placings in single quadrats (Figure 4c). I.e., suppose a species is dominant in the whole mixture at a dry weight proportion of say 40%, then in the case of Poisson-distributed species and large sampling quadrats, it will occupy all first ranks at a dry weight proportion of approximately 40%, which is much less than the 70% of the first coefficient of DWR.

The clumped occurrence of species (species in patches; compare Figure 1b) causes that even in mixtures with strong dominance of one species, all species, and thus also those of low dry weight proportions can compete successfully for first, second and third ranks. This means for all species together that their first ranks are becoming more proportionately distributed according to their dry weight proportions (illustrated for the patch size of 13.8 dm^2 in Figure 5a), and second, that in all species the almost always occurring over- and underestimations caused by the coefficients of DWR (for the patch size of 13.8 dm^2 illustrated in Figure 5e), partly compensate each other. Both phenomena are responsible for the better estimations of dry weight proportions from DWR.

Figures 5a, b, c (and d), (compare also Figures 4a and b), show that the relationships between the rank proportions and dry weight proportions are curved. The first rank proportions show an S-curve, the second and third rank proportions show single-peaked curves when plotted against the whole mixture dry weight proportions. The rank proportions are dependent on one another, which means that it is logical that when the proportion of first ranks increases to 100%, the second and third rank proportions decline to zero. I compared the curves obtained from simulation with curves from original field data and concluded that the program simulated field samplings very realistically. This was also supported by the realistic DWR coefficients calculated from simulation, from a multiple linear regression. Those of the patch size of 9.1 dm^2 were very good mimics of the original DWR coefficients. Because the rank proportions are mutually dependent, it is not surprising beforehand that a linear regression through the curved relationships works well. For all sampling cases with patches, high values were found for R^2 (0.983 - 0.989).

Important is the clear suggestion from Figure 1 that although pattern seems a condition for the good functioning of DWR, only a small amount of patchiness is necessary, and probably in most vegetations this condition is fulfilled. This role of patches could explain why quadrat size is relatively unimportant indeed, and could remove the still existing uncertainty about the role of pattern and horizontal vegetation structure in DWR.

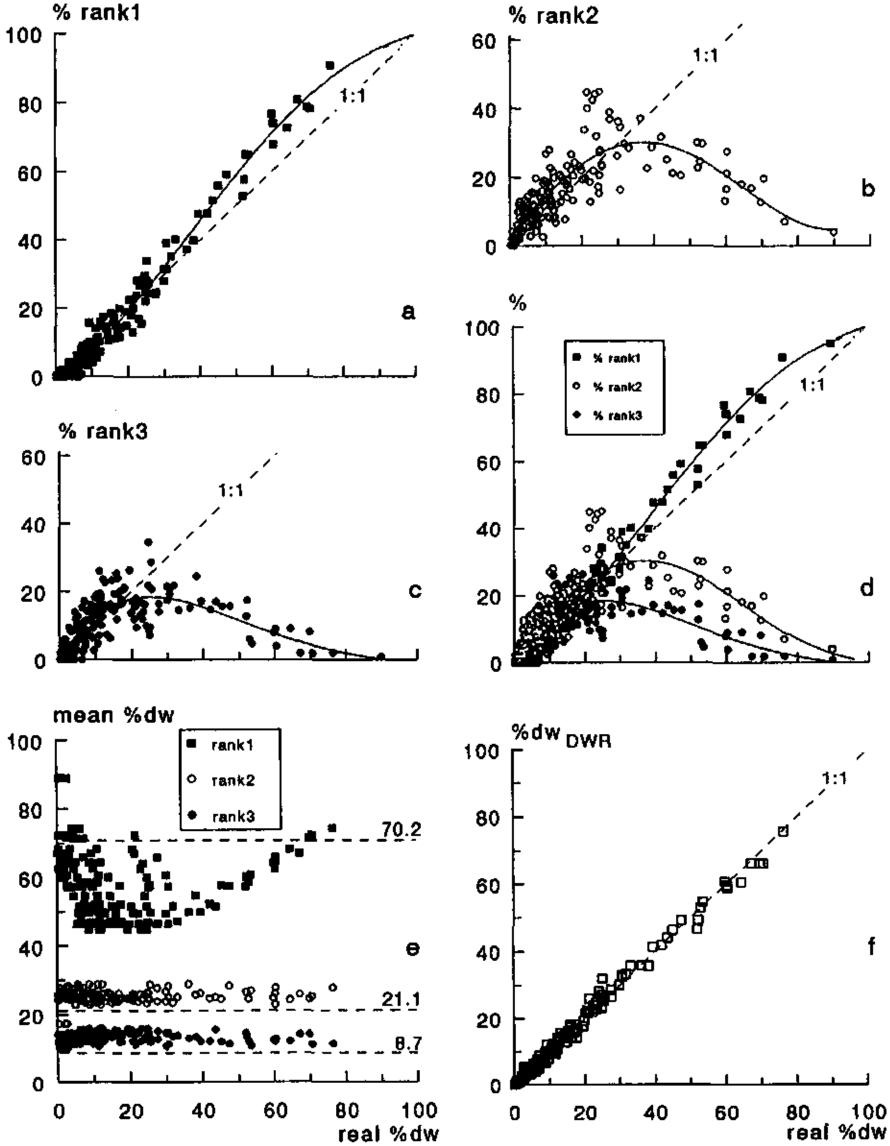

Figure 5. More detailed sampling data of the mixtures with species in patches of 13.8 dm². Plotted against the whole mixture dry weight proportions of the species are: (a-d) the rank proportions (%rank1 (a), %rank2 (b), %rank3 (c) and all three rank proportions (d)); (e) the actual percentages dry weight species received at first, second and third placings in single quadrats and (again) (f) the whole mixture dry weight proportions estimated from DWR and corrected for missing ranks.

The DWR method was originally developed for estimating dry weight proportions in forages where the Jones and Hargreaves' (1979) yield correction is essential. I think the method is also suited for studying vegetation changes, especially in floristically diverse grasslands with dominant species in not too high dry weight proportions. In cases where primarily ecological information is wanted, DWR estimations could be executed in early spring or in the autumn when patchwise differences in yield are relatively small. This would simplify the method because in that case no yield correction would be strictly necessary and moreover this would avoid the problem of estimating dry weight proportions in tall grass.

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Utilisation and losses of nitrogen in grazed grassland

H.G. van der Meer

Research Institute for Agrobiology and Soil Fertility (AB-DLO),
P.O. Box 14, 6700 AA Wageningen, The Netherlands

Abstract

In the past, N response studies on grassland concentrated on cutting experiments. However, the applicability of the results of this work on commercial farms has been questioned and recent research has been more concerned with responses to applied N under grazing in comparison with cutting. The purpose of this paper is to discuss the results of experiments conducted on an old sandy soil near Wageningen and a recently reclaimed loamy soil in Flevoland to compare the response of herbage yield to applied N under grazing and cutting and to assess the fate of applied N. At both sites, rates of N application to the cut and grazed swards were about 250, 400, 550 and 700 kg ha^{-1} $year^{-1}$; the cutting experiments also included control plots without N application.

In all cases, the response of herbage yield to applied N on the grazed plots was considerably smaller than on the cut plots. This resulted from a relatively high dry matter yield at the lowest rate of N application, a lower apparent recovery of applied N, a smaller effect of absorbed N on herbage yield and a considerably lower maximum herbage yield under grazing in comparison with cutting. These differences were caused by specific (positive and negative) effects of grazing as well as by the fact that net herbage yields under grazing (i.e. herbage intake) were compared with gross yields under cutting. The comparison of gross and net herbage yields and the too high lowest N rate on the grazed plots hamper a proper calculation and comparison of the optimum rates of N under grazing and cutting in these experiments.

Soil inorganic N was monitored on the grazed plots on the sandy soil during 5 years. There was a regular pattern of accumulation of inorganic N in the growing season and loss during the winter. In particular at the highest rates of N application, estimated nitrate losses in drainage water did not account for the losses of inorganic N from the soil layer of 0 - 60 cm. Nitrogen losses by denitrification in the top soil amounted to 1 - 3% of fertilizer N applied.

Small-plot experiments were conducted on a sandy soil to assess the fate of animal excreta after application to grassland. The proportion of urinary and faecal N lost by volatilisation of ammonia was, on average, 13%. Other rapid losses of urine N were observed. These averaged about 30% of urine N and appeared to be associated with nitrification. The remaining part of urinary N, on average about 55%, was recovered in the herbage or as residual inorganic N in the soil layer of 0 - 60 cm.

The results obtained were used to draw up N balance sheets of the grazed plots on the sandy soil. Between 30 and 40% of applied fertilizer N was not accounted for. This suggests accumulation of organic N in the soil, denitrification in deeper soil layers and underestimation of nitrate leaching. Despite intensive research, it is not yet possible to account for all N losses from grazed grassland.

Introduction

In his inaugural lecture at the Wageningen Agricultural University, 't Mannetje (1983) mentioned three research priorities related to the application of nitrogen (N) to Dutch grasslands:

- To assess the optimum rate of N application in grazing or whole-farm experiments that should extend over a period of several years to take account of positive or negative effects on sward quality. Up to then, N response on grassland had been studied almost exclusively in cutting experiments, often during a short period on a selected good sward.
- To study the best distribution of N over the growing season. 't Mannetje stated that the recommended decrease of the N rate in the course of the season was not based on experimental evidence.
- To explore the possibilities to replace fertilizer N by legumes. In this respect, he advocated the use of lucerne to replace grass and maize silage.

These points indicate doubts about scientific evidence of common practices of N application to grassland in The Netherlands. 't Mannetje stressed the need to reduce variable costs on dairy farms in a situation of decreasing milk quota and milk prices. He expected to accomplish this by avoiding a too liberal use of artificial fertilizers and concentrates. More recently, concern about negative effects of intensive ruminant production systems on the environment has also stimulated a critical assessment of the levels of fertilizer and concentrate use (van der Meer, 1982; Aarts et al., 1988; Aart et al., 1992; 't Mannetje and Paoletti, 1992; 't Mannetje, 1994; van der Meer and van der Putten, 1995).

In 1984, 't Mannetje initiated a joint research project to compare herbage yield response to applied N under grazing and cutting and to study N flows and losses in grazed grassland. This paper summarizes and discusses the main results obtained.

Herbage yield response to applied N under grazing and cutting

The research project mentioned in the Introduction was mainly carried out at two experimental farms of the Wageningen Agricultural University, viz. the A.P. Minderhoudhoeve at Swifterbant in Eastern Flevoland, and the Meenthoeve at Achterberg near Wageningen. The A.P. Minderhoudhoeve is situated on a calcareous silty loam, reclaimed in the 1950's. The experimental fields had been under grass for more than 20 years, but were resown with *Lolium perenne* cv. Wendy in 1985. Herbage yield response to applied N was assessed under continuous grazing by dairy cows, and under cutting at a dry matter yield of approximately 2000 kg ha^{-1} and in the first year (1986) also under weekly cutting. Rates of N application were 250, 400, 550 and 700 kg ha^{-1} year^{-1}. The cutting experiment included control plots without N application. The Meenthoeve is situated on a sandy soil with a moderate organic matter content. The old permanent grassland on the experimental fields had been resown in 1981 with a mixture of the *Lolium perenne* cvs. Splendor, Pelo and Vigor. At this site, herbage yield response to applied N was assessed under rotational grazing by steers, and under cutting at a dry matter yield of approximately 2000 kg ha^{-1}. Rates of N application were the same as in the experiments at the A.P. Minderhoudhoeve. Experimental methods at the two sites have been described extensively by Deenen (1994).

Effects of the grassland utilisation system on the response of herbage yield to applied N are conveniently analysed by means of the so-called three quadrants diagram, which interrelates supply of N, N uptake in the herbage and herbage yield (Figure 1). This method of analysis is based on the fact that the effect of applied N on herbage yield (quadrant II) depends on the proportion of applied N absorbed by the crop (N yield in the herbage, quadrant IV), and the effect of absorbed N on herbage yield (quadrant I). It has been shown elsewhere (van der Meer and van Uum-van Lohuyzen, 1986) that the shape of the N response curve depends on:

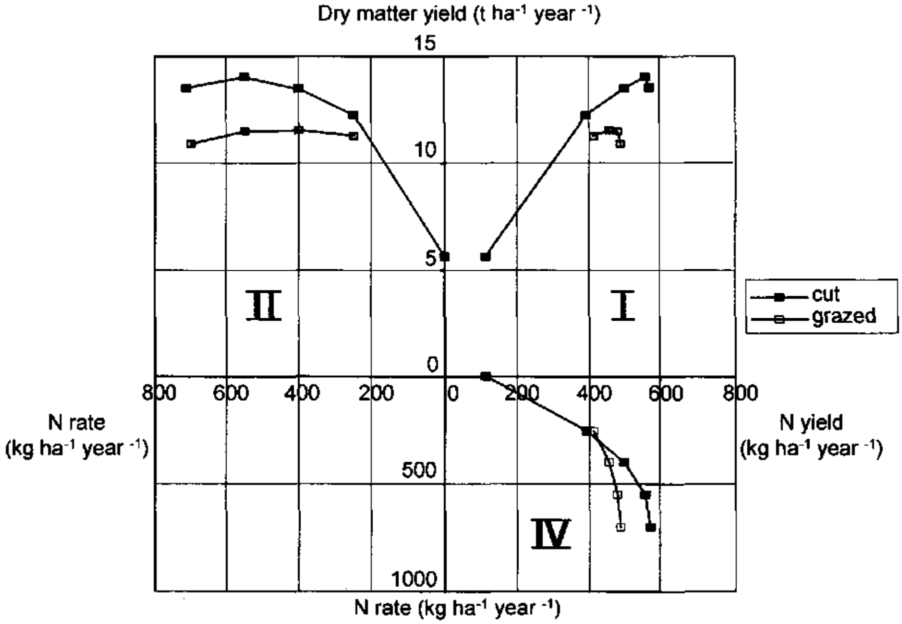

Figure 1. The effect of the rate of N application on N uptake and herbage yield under cutting and rotational grazing with steers on the sandy soil in 1987. For cutting, results are averages of 4 replicates, and for grazing of 2 replicates (Deenen, 1994).

- the uptake of N from other sources than fertilizer or slurry, viz. from soil reserves, atmospheric deposition, biological fixation and urine and dung from grazing animals (shown by the intercept of the lines in quadrant IV);
- the apparent recovery of applied N (ANR), i.e. the proportion of applied N harvested in the herbage (shown by the slope of the lines in quadrant IV);
- the N concentration in the harvested herbage, i.e. the reciprocal of the dry matter yield per kg N harvested (quadrant I), and
- the maximum dry matter yield (quadrant I).

Grazing, compared to cutting, probably affects these aspects as follows:

- Excreta of grazing animals increase N supply. This may enhance N yield in the herbage at nil fertilizer N, and also ANR because of the increasing production of urine N at increasing rate of N application.
- Grazing animals generally harvest a smaller part of the above-ground biomass than the cutting machine, because they leave longer stubbles and refuse herbage around dung pats. Longer stubbles and herbage residues may enhance regrowth, but most probably reduce the harvest index for N and, hence, N yield at nil fertilizer N as well as ANR. A part of the N in stubbles and herbage

residues will be utilised by regrowths later in the season, but another part will be added to the pool of organic N in the soil.

- Under grazing, herbage generally is harvested in a younger stage of growth and, consequently, with a higher N content (Sibma and Alberda, 1980). This, together with negative effects of the grazing animals on the sward by treading, poaching, fouling and urine scorching, will reduce dry matter yield at all levels of N uptake, as well as maximum dry matter yield.

In both experiments conducted by the former Department of Field Crops and Grassland Science of the Wageningen Agricultural University, herbage yields under grazing were lower and responded less to applied N than under cutting (Deenen, 1994). On the calcareous silty loam at Swifterbant, this was caused by a slightly lower N yield at the lowest rate of N application (250 kg ha^{-1} $year^{-1}$), a considerably lower ANR, and a lower yield of dry matter or net energy for lactation at all levels of N uptake. Under grazing, average marginal ANR values over the years 1986, 1987 and 1988 were 63, 40 and 13% of the extra N applied for the increments 250 to 400, 400 to 550 and 550 to 700 kg N ha^{-1} $year^{-1}$, respectively. Unfortunately, Deenen did not specify ANR values obtained in the cutting experiment, but only indicated that they varied between 80 and occasionally more than 100% for all rates of N application. However, the three quadrants diagrams presented in his thesis, show considerably lower values for the increment 550 to 700 kg N ha^{-1} $year^{-1}$. The mean apparent nitrogen efficiency values (ANE; van der Meer *et al.*, 1987) for the increments of N application mentioned, were 9.7, 6.5 and 1.9 kVEM per extra kg N under grazing (VEM is the unit for net energy for lactation in the Dutch feed evaluation system; 1 VEM = 6.9 kJ), and 17.6, 10.6 and 5.8 kVEM per extra kg N under cutting (Deenen, 1994).

On the sandy soil at Achterberg, there was no response to N application above the lowest rate of 250 kg ha^{-1} $year^{-1}$ under rotational grazing with steers, whereas under cutting herbage yields increased up to an annual application rate of approximately 550 kg N ha^{-1} (Figure 1). Deenen (1994) attributed the lack of response to higher N rates under grazing to negative effects of poaching and urine scorching on the sward, which increased at the higher N rates. However, the rather small response in the cutting experiment to annual N rates of more than 250 kg ha^{-1} (Figure 1) also indicates less favourable growing conditions at Achterberg than at Swifterbant. Figure 1 confirms the findings in the experiment at Swifterbant, viz. on the grazed fields a relatively high herbage yield at the lowest rate of N application, a lower ANR, and a smaller effect of absorbed N on herbage yield than under cutting.

With respect to the differences between cutting and grazing, it should be taken into account that in the experiments discussed here, the response to applied N has been expressed in terms of harvested herbage. Under cutting, this was the gross herbage yield, i.e. all the herbage harvested by cutting at a height of 4 - 5 cm. Under farming conditions, there will be losses after cutting, associated with the field period, harvesting, conservation and feeding, and only a part of the gross yield will be utilised by the animals. There is no information on the effect of the rate of N application on these losses and on the proportion of cut herbage finally utilised by the animals. Under grazing, harvested herbage was the net yield, i.e. the herbage consumed by the animals. Here, "harvesting and feeding losses" were not included in the yield.

In other comparisons of herbage yield response to applied N under cutting and grazing, herbage yield under grazing has been assessed by measuring accumulated herbage at the start of grazing (e.g. Boxem, 1973; Benke, 1992). In these studies, strips were cut and sampled only before turning in the animals to the fields and no estimates were made of herbage growth during grazing and of herbage residues. As a consequence, these experiments did not provide information on the utilisation efficiency of accumulated herbage, which may be affected by grazing management, soil and weather conditions and rate of N application (Deenen, 1994). Therefore, it is difficult to draw practical conclusions from these comparisons.

In some studies, defoliation frequency may have affected the observed differences in N response between cutting and grazing. In the experiments at Swifterbant and Achterberg, harvesting frequencies on the cut and grazed fields were independent and determined by growth rate and target yields at harvest, assuring good management for each grassland utilisation system and N rate (Deenen, 1994). In the studies of Jackson and Williams (1979) and Benke (1992), all experimental treatments were harvested on the same dates, which will be sub-optimal for some treatments and affect the shape of the N response curves and the differences between cutting and grazing.

Deenen (1994) calculated "optimum" rates of N application, assuming a marginal profitability of 7.5 kg dry matter per kg N applied. However, because he determined gross herbage yield under cutting and net yield under grazing, it is not correct to use the same marginal profitability for both grassland utilisation systems. Hence, Deenen overestimated the difference in "optimum" N rate between cutting and grazing (about 200 kg ha^{-1} $year^{-1}$). In addition, the lowest rate of N application to the grazed plots at Swifterbant and Achterberg was too high to calculate accurate N response curves and optimum N rates.

The marginal profitability of 7.5 kg dry matter per kg N applied, used in the calculations of Deenen, has been proposed by Prins (1983) as the average of different values reported in literature. Several authors have used this value in later studies without taking account of the factors affecting marginal profitability, like herbage quality, grassland utilisation system, management factors affecting utilisation of gross yield, and farm structure and management (Mooij and Vellinga, 1992; Deenen, 1994). After determining herbage yield response to applied N, more attention should be given to a correct interpretation and use of the results.

The experiments at Swifterbant and Achterberg have shown a consistently smaller response of herbage yield to applied N under grazing than under cutting. Probably, this smaller response was partly caused by the fact that under grazing net herbage yield had been determined and under cutting gross herbage yield. However, the relatively high herbage yields at the lowest rate of N application, and the lower apparent recoveries of applied N and maximum herbage yields under grazing in comparison with cutting (Deenen, 1994), also point to specific positive and negative effects of grazing on the response to applied N. These specific effects may lead to a lower optimum N rate under grazing, even if a lower marginal profitability is observed than under cutting. Model calculations, as proposed by Mooij and Vellinga (1992), may be used for a further analysis of specific effects of grazing on the response of herbage yield to applied N and on the optimum rate of N application.

Nitrogen losses from grazed grassland

The experiments at Swifterbant and Achterberg, discussed in the preceding paragraph, also have been used to quantify N flows and losses ('t Mannetje and Jarvis, 1990). Here, the main results of the work on the sandy soil at Achterberg will be presented. In the grazing experiment, we monitored the amount of residual inorganic N in the soil layer of 0 - 60 cm at each rate of N application. For this purpose, soil samples were taken four times a year, viz. just before fertilizer application in spring, in the second half of June, in the second half of August, and immediately after the last grazing in late October or early November. Soil sampling in June and August was always carried out immediately after grazing and before fertilizer application. Each time, the experimental treatments were sampled in quadruplicate. The replicates consisted of 12 to 15 cores of about 4 cm diameter, taken at random from the field. These cores were divided into layers of 20 cm to give 3 sub-samples per replicate. Sub-samples were analysed individually for ammonium and nitrate N. The results are presented in Figure 2.

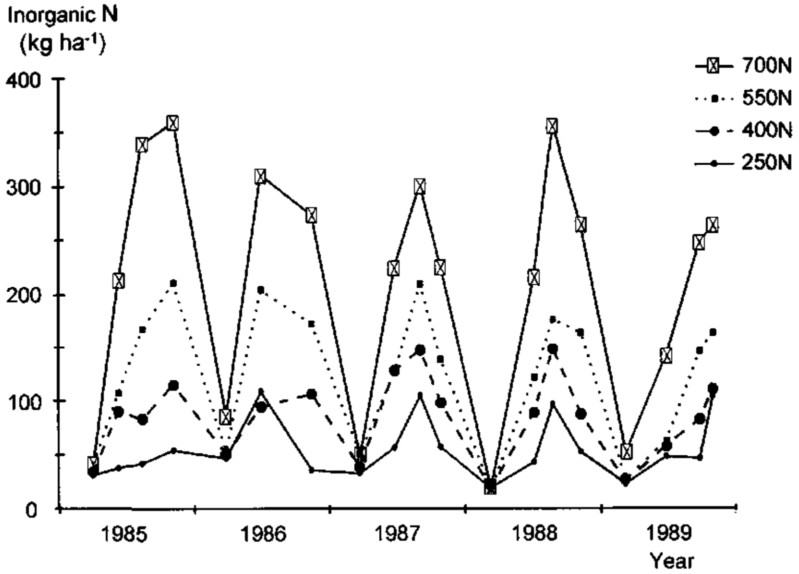

Figure 2. The effect of the rate of N application on the content of inorganic N in the soil layer of 0 - 60 cm under the grazed swards on the sandy soil (H.G. van der Meer and A.H.J. van der Putten, unpublished results).

Figure 2 shows a regular pattern of accumulation of inorganic N in the growing season and loss during the winter. Rate of N application had a large effect on accumulation, in particular in 1985 and 1988 when the additional N of the increment 550 to 700 kg ha^{-1} $year^{-1}$ was completely recovered as soil inorganic N in late August and early November (Figure 2). Generally, the total content of inorganic N in the soil layer of 0 - 60 cm was highest in August and decreased in the last 2 months of the growing season. Probably, this decrease was caused by denitrification in the deeper soil layers and/or leaching losses associated with the precipitation surplus in autumn. Analysis of the distribution of inorganic N over the three sampled soil layers of 20 cm showed a downward movement of nitrate during the whole growing season in all the experimental years (H.G. van der Meer and A.H.J. van der Putten, unpublished results). In fact, there was already a significant increase of inorganic N in the layer 40 - 60 cm in the second half of June. This suggests that N leaching losses even may occur during the drier part of the growing season.

Estimates of nitrate leaching losses from the tile-drained experimental plots in the years 1986/1987, 1987/1988 and 1988/1989 (J.H.A.M. Steenvoorden, unpublished results; Macduff *et al.*, 1990), however, gave lower values than expected on the basis of the amounts of inorganic N in the soil layer of 0 - 60 cm. Nitrate leaching was calculated as the product of nitrate concentration in tile effluent and drainage volume, estimated from a hydrological mass balance in time steps of 1 - 10 days. Calculated leaching losses from the grazed plots receiving 250, 400, 550 and 700 kg N ha^{-1} $year^{-1}$ were 48, 61, 116 and 141 kg N ha^{-1} $year^{-1}$, respectively. The corresponding amounts of inorganic N in the soil layer sampled in early November of these years were 48, 97, 157 and 253 kg ha^{-1} (Figure 2). These data and presumed nitrate losses from the soil layer of 0 - 60 cm during the growing season indicate that only a fraction of accumulated inorganic N was accounted for in drainage water. The fate of the other fraction is not clear. Probably, denitrification in the deeper soil layers caused some N losses. In addition, it is possible that the rather complicated hydrological situation of the experimental fields hampered a correct calculation of drainage volume, causing underestimation of leaching losses.

During the growing seasons of 1989 and 1990, de Klein and van Logtestijn (1994) conducted denitrification measurements on the grazed experimental plots at Achterberg receiving 250 and 400 kg N ha^{-1} $year^{-1}$. Estimated denitrification losses in the top soil layer of 11 cm were 2.7 and 5.4 kg N ha^{-1} in 1989, and 7.6 and 8.4 kg N ha^{-1} in 1990. So, these losses ranged between 1.1 and 3.0% of fertilizer N applied and were not significantly affected by N application rate (de Klein and van Logtestijn, 1994).

The return of N in excreta strongly affects N flows and losses in grazed pasture. Grazing ruminants generally excrete more than 75% of ingested N in faeces and urine (Whitehead, 1970; van der Meer, 1982). The steers grazing the experimental plots at Achterberg in 1986 and 1987 excreted approximately 80 - 90 kg N ha^{-1} $year^{-1}$ in faeces, and 250 - 400 kg N ha^{-1} $year^{-1}$ in urine (Deenen, 1994). Rate of N application hardly affected N excretion in faeces and moderately increased N excretion in urine.

The fate of urinary and faecal N, voided by grazing animals, was studied simultaneously with the experiments at Achterberg in small-plot experiments under similar soil and weather conditions at the experimental farm Droevendaal near Wageningen (Vertregt and Rutgers, 1988; van der Meer and van Uum-van Lohuyzen, 1989; van der Meer and Whitehead, 1990). This research was carried out with artificial urine, containing 12 g N l^{-1}, and fresh faeces, containing 13.8% dry matter and 0.392% total N. Urine and faeces were applied at rates of 5 l m^{-2} and 32 kg m^{-2}, respectively, to plots of about 1 m^2 covered with a short dense sward dominated by *Lolium perenne*. Ammonia volatilisation was always measured continuously during the first 10 days after application of urine or faeces, and in some cases for longer periods. Soil inorganic N was measured immediately before and 10 days after urine application, and at the end of the growing season after the last cut. The average results of 10 applications of artificial urine in 1986 are presented in Table 1.

Table 1. Apparent recovery of urinary N in (A) the first 10 days, or (B) the remaining part of the growing season after application to grassland on a sandy soil near Wageningen. The values are average results of 10 experimental plots, established between the end of April and early July, with application of artificial urine at a rate of 60 g N m^{-2}. The results of untreated control plots were used to calculate "net effects" of urinary N.

Flow or pool	Recovery of urinary N (%)	
	average	range
(A) in the first 10 days:		
Ammonia volatilisation	10	4 - 17
Crop uptake	4	-1 - 9
Soil inorganic N	58	42 - 74
Not accounted for	28	6 - 48
(B) in the remaining part of the growing season:		
Ammonia volatilisation	13	5 - 22
Crop uptake	44	22 - 60
Soil inorganic N	9	-1 - 39
Not accounted for	34	24 - 47

Table 1 shows that 10 days after urine application, on average, 62% of applied N was recovered in the herbage and as inorganic N in the soil profile of 0 - 60 cm, whereas 10% had been lost by ammonia volatilisation and 28% could not be accounted for. The proportion of inorganic N not accounted for after 10 days ranged from 6 to 48%. Analysis of this variation revealed a negative correlation between the amount of ammonium N in the soil profile after 10 days and the amount of N not accounted for (van der Meer and Whitehead, 1990). This may point to N losses associated with nitrification. De Klein and van Logtestijn (1994) measured denitrification and nitrous oxide (N_2O) emission after application of artificial urine (40 g N m^{-2}) to a *Lolium perenne* sward on the sandy soil at Achterberg. During 14-day periods following urine applications in May and June, N losses by denitrification amounted in both cases to 18% of urine N applied, whereas N_2O emission losses were 16 and 8%, respectively. To estimate total N_2 + N_2O losses, the origin of the N_2O must be known. If denitrification was the only source of N_2O, total N_2 + N_2O losses would be 18%. However, if nitrification was the only source of N_2O, total N_2 + N_2O losses would range between 26 and 34%

of urine N. These values are of the same magnitude as the proportion of urinary N not accounted for in Table 1.

In the remaining part of the growing season after urine application, N recovery in the harvested herbage averaged 44% of urine N (Table 1). From urine applications after the beginning of June, N recovery in the harvested herbage decreased and inorganic N in autumn increased (van der Meer and Whitehead, 1990). Soil inorganic N in autumn was mainly nitrate N and was completely lost during the following winter, probably both by denitrification and leaching.

The average proportion of faecal N lost by ammonia volatilisation from 2 experimental "dung pats" of 1 m^2, established on 1 July 1987 at the experimental farm Droevendaal, was 13% (van der Meer and Whitehead, 1990). Topped grass tillers, planted on 27 August 1987 on these "dung pats", absorbed almost 8% of faecal N in the remaining part of the growing season of 1987 and 4.5% in the growing season of 1988. About 5.5% of faecal N was recovered as inorganic N in the soil profile in the autumn of 1987 and was probably lost during the following winter. The swards did not show a residual effect of applied dung N in 1989. This indicates that a large part of the dung N, probably about 70%, was rather stable organic N.

Nitrogen balance sheets of cut and grazed grassland

Based on information reported by Deenen (1994) and in the preceding paragraph, N balance sheets have been drawn up for the different experimental treatments at Achterberg (Tables 2 and 3).

Table 2. The effect of the level of fertilizer N on the N balance sheet of cut grassland at Achterberg. Figures are in kg N ha^{-1} in 1987.

	Level of fertilizer N				
	N0	N1	N2	N3	N4
N inputs:					
Soil inorganic N in spring	25	33	38	51	48
Fertilizer	0	250	400	550	700
Total	25	283	438	601	748
N outputs:					
Harvested herbage	111	415	535	632	645
Soil inorganic N in autumn	20	19	32	67	96
Total	131	434	567	699	741
Not accounted for	-106	-151	-129	-98	7

Under cutting, N output in harvested herbage and as soil inorganic N at the end of the growing season exceeded N input as soil inorganic N in spring and in fertilizer, except at the highest rate of N application (Table 2). This is caused by the fact that the N supply by atmospheric deposition and mineralisation of soil organic N has not been included. At this site, these processes probably contribute about 160 kg N ha^{-1} $year^{-1}$ to the N yield in the harvested herbage (Deenen, 1994). Addition of this N supply to the N inputs results in amounts of N not accounted for ranging from 9 to 167 kg N ha^{-1}. The amounts of N not accounted for, calculated in this way, indicate that considerable N losses during the growing season only occurred on the plots with the highest rate of N application. Probably, these losses were caused by denitrification and nitrate leaching.

The following assumptions were made to calculate the N balance sheets of the grazed plots (Table 3):

- Nitrogen in liveweight gain: 30 g N per kg gain (Lantinga *et al.*, 1987).
- Ammonia volatilisation: 13% of N excreted in faeces and urine (Vertregt and Rutgers, 1988; Table 1); amounts of excreted N were reported by Deenen (1994).
- Denitrification of fertilizer N: 3% of applied N (de Klein and van Logtestijn, 1994).
- Undefined losses of urine N: 30% of urine N produced (Table 1).

Table 3. The effect of the level of fertilizer N on the N balance sheet of grazed grassland at Achterberg. *Figures are in kg N ha^{-1}, and averaged over 1986 and 1987.*

	Level of fertilizer N			
	N1	N2	N3	N4
N inputs:				
Soil inorganic N in spring	40	44	52	66
Fertilizer	268	406	517	672
Total	308	450	569	738
N outputs:				
Liveweight gain	27	27	27	22
Removed herbage residues	15	14	12	17
Ammonia volatilisation	47	53	56	56
Denitrification of fertilizer N	8	12	16	20
Undefined losses of urine N	84	97	103	106
Soil inorganic N in autumn	46	102	155	249
Total	227	305	369	470
Not accounted for	81	145	200	268

Table 3 shows that on the grazed plots, N inputs exceeded measured plus estimated N outputs at all rates of N. This is a remarkable difference with the N balance sheets of the cut plots (Table 2). The positive values of N not accounted for indicate (net) accumulation of organic N in the soil and, probably, underestimation of N losses from the system, in particular at the higher rates of N application. Hassink and Neeteson (1991) reported an increase of organic N of about 50 kg ha^{-1} $year^{-1}$ in the top 10 cm of the soil of the grazed plots. This amount was not affected by the rate of N application and is slightly lower than the stable fraction of faecal N, estimated at about 60 kg ha^{-1} $year^{-1}$ (70% of faecal N). Because N inputs and N outputs in the Tables 2 and 3 only relate to the period between fertilizer application in spring and the last grazing in autumn, the amounts of N not accounted for also refer to this period. In the preceding paragraph, it was concluded that downward N losses from the soil occurred during the growing season (Figure 2 and related discussion). This points to denitrification in deeper soil layers and underestimation of nitrate leaching. However, it is difficult to accept that these losses explain the large values of N not accounted for.

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Stocking rate and sustainable grazing systems

K.G. Rickert

Department of Plant Production, University of Queensland, Gatton Campus, Gatton, Q4343, Australia

Abstract

The influence of stocking rate on the ecological and economic sustainability of grazing systems is discussed. The maximum, long-term stocking rate that does not cause pasture degradation is called the maximum sustainable stocking rate (SSR) to avoid confusion with two related but poorly defined terms, carrying capacity and grazing capacity. SSR is based on critical levels of utilisation which should be qualified by a probability rating for the reliability of local climate. Levels of critical utilisation differ across pasture types, being lowest in ecologically sensitive arid systems and highest in sown temperate pastures.

Production per animal against stocking rate was expressed by a 3-phase linear model for a wide range of grazing systems. Each phase had both biological and managerial implications: Phase 1 was the potential production per animal; Phase 2 exhibited a linear decline in production per animal as stocking rate increased; and Phase 3 displayed the influence on production per animal of changes in botanical composition at high stocking rates. The junction of Phase 2 and 3 indicated SSR. Also, the slope of the Phase 3 indicated the impact of pasture degradation on animal production. The slope increased sharply when degradation was accompanied by loss of basal cover and increase in weeds, but the change in slope was much less when stoloniferous species replaced tufted species.

The relative magnitude of stocking rates for highest profit and SSR reflected the likelihood of profit maximisation leading to pasture degradation. Evidence suggested that for beef production, where carcass quality and price are inversely related to stocking rate, the most profitable stocking rates are less than SSR. However, when fibre quality and price of product are directly related to stocking rate, the most profitable stocking rates for fibre production are likely to approach SSR. Both production systems offer flexible management, since near maximum profits occur over a range of stocking rates. Reports from several farmers support the view that low stocking rates enhance ecological and economic sustainability of grazing systems in variable climates.

The knowledge, skill and attitudes of a manager are key elements in sustainable grazing systems. Attitudes on what constitutes variable costs influence the choice of stocking rate because economic conventions that generate low variable costs encourage higher stocking rates than conventions with high variable costs. Also, attitudes towards risk influence the choice of stocking rate, since reliability of production decreases with increasing stocking rate. In good economic conditions, the risk factor is likely to encourage low stocking rates, but in depressed economic conditions, risks associated with high stocking rates are more difficult to avoid and land degradation is more likely, particularly when variable costs are perceived to be low. Ecological sustainability should benefit from destocking as a drought management strategy, rather than supplementary feeding.

Public demands are increasing for grasslands to be a source of fresh water and a control measure for emission of greenhouse gases. Both processes are influenced by stocking rate.

Introduction

It is fitting on an occasion that honours the contribution Professor Leen 't Mannetje has made to pasture science for a paper to focus on the pasture/animal interface, the interactions between two basic components of a grazing system: the forage and the grazing animal. Stocking rate receives particular attention, because it has a profound influence on the level and quality of animal production, has an impact on the sustainability of grazing systems and is a management option that can be readily changed. Furthermore, Leen 't Mannetje has recognised the importance of stocking rate and studied its influence on pasture and animal production in Australia, Europe and Latin America. This paper reviews the interaction between stocking rate and animal production, making reference to tropical and temperate pastures with and without legumes. It attempts to identify principles that underpin sustainable production from the wide range of commercial grazing systems. In this regard, a sustainable system must have desirable biological properties and be economically viable. Because of its focus on sustainable production, emphasis is given to results from long-tern grazing trials and output from computer models that simulate temporal trends in grazing systems.

Terminology and Concepts

Since grazing is a worldwide activity that involves different countries, types and breeds and classes of livestock, animal products, types of forage and time scales, it is not surprising that terminology and units describing grazing systems vary across local and scientific communities. Heady and Child (1994) clarified the definitions, and this paper follows their recommendations with a few notable exceptions as described below.

Stocking rate is the number of animals per unit area supported for a season or year by a management unit such as a field, a common or a farm. For technical purposes the preferred unit is head per hectare (hd/ha), because it is suited for plotting responses to stocking rate (Shaw, 1970). However, workers in extensive grazing systems often find head per km^2, or the inverse (ha/hd), more convenient terms, because they avoid referring to a fraction of an animal. The former term (hd/ha) is used in this paper, because of emphasis on stocking rate responses. Another difficulty in expressing stocking rate arises when more than one type or class of animal graze a management unit together, such as cows and calves or cattle and sheep. This problem is overcome by converting the different animal types to a convenient standard animal unit. The conversion factors usually reflect the metabolic weights ($LW^{0.75}$, where LW = liveweight kg/hd) of each type of animal relative to the standard animal. However, the choice of standard animal reflects the needs and interest of local workers. For example, workers in wool producing regions of Australia use dry sheep equivalents, while regions producing cattle use the term adult equivalents. A convenient standard unit (AU) is the metabolic weight of a mature non-lactating cow of 500 kg liveweight (Minson and Whiteman, 1989) which may be further qualified by a specification for performance or intake for the production system being considered (Heady and Child, 1994). Whilst the AU term is suitable for domestic livestock, it is not applicable to grazing systems that involve ungulate populations, such as African savannas grazed by elephants, buffalo and several antelope species. Under these circumstances stocking rate is expressed as LW/km^2 or $LW^{0.75}/km^2$ (de Bie, 1991). However, Scarnecchia (1986) argues that energy-based conversion factors have limited usefulness, as they are not animal-unit-equivalents that reflect the differences in dietary composition across species or classes of grazing animals. The following two common terms are closely allied to stocking rate.

Stocking density (sometimes called stocking intensity) is the ratio of animals to land area at an instant in time, rather than a season or year as for stocking rate. The distinction is illustrated in rotational grazing systems. If a farm of area A_f consists of several paddocks each of area A_p, that are rotationally grazed by N_a animals, then the stocking rate for the farm is constant at N_a / A_f, but the stocking density for each paddock changes regularly and is given by N_a/A_p.

Carrying capacity is the long-term maximum stocking rate for a management unit that meets a goal in animal production without deterioration of the production system. It is a vital concept for managed grazing systems that incorporates the biological, commercial and social elements pertaining to good land care. It is commonly used to quantify a farm for sale or leasing in Australia and USA. When forage growth displays strong seasonal variation, and drinking water is available, carrying capacity is largely determined by the feed supply in the season of greatest stress. Furthermore, efforts to increase carrying capacity concentrate on improving the feed supply in the stressful period (e.g. augmenting native pasture with a legume) or by changing the efficiency of converting forage into animal products (e.g. using a breed of livestock that is more adapted to the prevailing climate). In natural grazing systems the term **ecological carrying capacity** is often used to reflect a wildlife population per unit area of land that is in equilibrium with its habitat (de Bie, 1991). Heady and Child (1994) urge caution in using the term carrying capacity because it is widely misunderstood and Bartels *et al.* (1993), after reviewing a wide range of definitions, concluded the term was not relevant to grazing systems in Africa. Evidence of the confusion is provided by the following definitions. Holechek *et al.* (1995) focus on the condition of the forage resource by regarding carrying capacity to be the maximum stocking rate possible, year after year, without inducing damage to vegetation or related resources. Heady and Child (1994) expand this definition to include both the forage resource and animals by regarding carrying capacity to be the stocking rate that will meet an objective in animal performance without deterioration of the ecosystem over a long time period. However, Scarnecchia (1990) takes an even wider view and recommends a generalised definition for carrying capacity that can be customised for different production systems: 'the optimum stocking level to achieve specific objectives given specified management options'. In this paper the definition by Holechek *et al.* is preferred because it has a single focus, but to set it apart from the wider definitions of carrying capacity, and following the suggestion of McKeon *et al.* (1991), it will be called **maximum sustainable stocking rate** (SSR). Logically, maximum sustainable stocking rate could be regarded as the grazing capacity of a management unit, but since **grazing capacity** also has a confusing assortment of definitions (Bartels *et al.*, 1993), it too will not be used in this paper.

As stocking rate increases so does the amount of forage **utilisation** (U), defined by McKeon and Rickert (1984) as the proportion of forage growth that is consumed by grazing animals over a growing season (i.e., $U = \Sigma I / \Sigma G$ where ΣG is accumulated growth and ΣI is accumulated intake expressed as kg/ha). This definition of utilisation is related to intake in a generalised model of animal production (McKeon and Rickert, 1984) which has been used to simulate and analyse different production systems (McKeon *et al.*, 1991). Utilisation can be estimated by (i) using grazing exclosures to measure growth and estimating intake as the difference between observed growth and the change in forage yield during the growing season; (ii) estimating intake from animal performance (Minson and McDonald, 1987) and growth as the change forage yield plus intake; and (iii) estimating both growth and intake by a simulation model such as GRASP (McKeon *et al.,* 1991). Since the above definition is not universally accepted, caution is required when referring to utilisation. For example, W. Holmes (1987) includes forage consumed by non-agricultural fauna and litter decomposition in the definition.

Another approach to defining utilisation is reference to the number of plants that have been grazed or to the height of grazing (Heady and Child, 1994), but these approaches tend to focus on the converse of utilisation, **residue**: the yield of standing pasture remaining after grazing (kg/ha). Residue is important because it has an impact on the ability of plants to regrow after grazing, on the sustainability of a system by increasing infiltration and reducing soil erosion (Thurow *et al.*, 1988; Dunnin, 1987; McIvor *et al.,* 1995) and on fuel for fires that help to control brush (Hodgkinson *et al.,* 1984; Taylor, 1994). With respect to soil erosion and fuel for fires, the total yield of plant material should be considered including standing pasture, pasture litter and leaves from trees and shrubs rather than yield of standing pasture. The importance of minimising soil erosion, together with the impact of low forage yield on animal production, has led to recommendations that residues should not fall below a critical level that varies with the type of pasture and prevailing climate (Bartolome *et al.,* 1980; Taylor *et al.,* 1992). For example, in the rangeland of Texas and California a residue of 560 kg/ha is recommended (Heady and Child, 1994). With regard to fire, a residue of about 1500 kg/ka is needed to carry a fire in a dry season (Hodgkinson *et al.,* 1984; Burrows *et al.,* 1991) and stocking rates need to be adjusted to ensure sufficient residue if a fire is a management goal. McKeon et al. (1991) propose that the risk of feed shortages after burning can be reduced by using the Southern Oscillation Index in winter as an indicator of rainfall in the following spring. At a point in time the yield of standing pasture available per animal (kg/hd) is called the **grazing pressure**.

Over-utilisation leads to **degradation**, unwanted changes in the vegetation or soil components of a system that eventually lead to a decline in productivity or unacceptable side effects. Traditionally, the vegetation changes associated with degradation in extensive grazing systems have been viewed as shifts away from a climax or subclimax regime (Whalley, 1994), but in recent times 'state and transition models' (Westoby *et al.,* 1989) have provided a better expression of vegetation changes associated with degradation (Brown, 1994; Filet, 1994). The symptoms of degradation develop over long periods of time and vary across production systems. In rangeland the symptoms may include a decline in desirable species, an increase in undesirable species including annual weeds, a decline in basal area or plant cover, encroachment of woody weeds, increased soil compaction, and increased soil erosion (Pressland *et al.,* 1988; Heady and Child, 1994). In extreme situations most herbage plants die, leaving a bare soil surface exposed to the elements (Mott, 1985, 1987). A decline in animal production might accompany the vegetation changes (Taylor, 1990) but this may not be a sensitive indicator of degradation (Ash *et al.,* 1993) because it is confounded by year-by-year variation in climate, the capacity of an animal to compensate in growth when forage supply is plentiful, and by changing production technology such as using more adaptive livestock. Additional symptoms of degradation, which apply to intensive grazing systems that rely on inputs of fertiliser or legumes with high nitrogen fixation, are the rate of soil acidification (Haynes, 1983) and the loss of nutrients through volatilisation, runoff or deep drainage ('t Mannetje, 1994; van der Meer, 1994).

The preferred approach is to select one or more reliable indicators of degradation and then manage a grazing system to maintain the indicators within critical limits. In the rangeland of Queensland, botanical composition and basal area of herbage plants are regarded as indicators of degradation (Pressland *et al.,* 1988; McKeon *et al.,* 1991; Orr *et al.,* 1993; Scanlan *et al.,* 1994). In contrast, the concentration of NO_3^- in groundwater and amount of NH_3 volatilisation are indicators of unsustainable farming systems in Europe where governments have imposed targets that demand a holistic approach to nutrient cycling, a re-evaluation of type and management of pastures, and changes to farm stocking rates ('t Mannetje, 1994; Peel and Lloveras, 1994).

It follows from the above discussion that a **critical utilisation** is the maximum amount of utilisation that does not cause degradation of the pasture. In effect it is the level of utilisation that either retains sufficient proportion of previous growth to maintain the system's productivity, or retains sufficient residue to control soil erosion, whichever comes first, - a combination of the two approaches to utilisation mentioned above. A stocking rate that does not exceed critical utilisation in the long term is a sustainable stocking rate as defined previously (McKeon *et al.*, 1991). Subsequently, Scanlan *et al.* (1994) estimated maximum sustainable stocking rate for a farm as the stocking rate for continuously grazed adult steers that would result in less than 30% utilisation in 70% of years. The calculated maximum sustainable stocking rate was similar to estimates by farmers, but different to a rated maximum sustainable stocking rate by a government department. The approach was also novel in that maximum sustainable stocking rate was qualified by a probability rating which inferred some risk and flexibility in management - critical utilisation might be exceeded in 30% of years. However, severe drought still requires a special reduction in stocking rate to maintain plant cover and to foster herbage growth after the drought breaks (Mott and Tothill, 1984; Wilson *et al.*, 1984). The conventional approach is to estimate maximum sustainable stocking rate and critical utilisation from stocking rate trials. Values for critical utilisation differ across pasture types (Table 1), being least for arid woodlands and highest for sown temperate pastures. Also, within a climatic zone, pastures on infertile soils appear to have a lower critical utilisation than pastures on relatively fertile soils, as indicated by the critical utilisations for the infertile *Acacia aneura* woodlands compared to the relatively fertile *Astrebla* grasslands of western Queensland (Table 1).

Table 1. Examples of critical utilisation for different types of pasture.

Pasture type	Critical utilisation %	Source
Acacia aneura woodland	20	Orr *et al.*, 1993
Astrebla grassland	30	Wilson *et al.*, 1984
Eucalypt woodland	30	Scanlan *et al.*, 1994
Semidesert grass and shrubland	30-40	* Holechek *et al.*, 1995
Northern mixed prairie	40-50	* Holechek *et al.*, 1995
California annual grassland	50-60	* Holechek *et al.*, 1995
Sown temperate pasture	60-90	W. Holmes, 1987; C. Holmes,1987

* Selected from the 17 types of rangeland listed in Table 8.7, p. 195.

Stocking Rate and Animal Production

Production per animal

A conceptual relationship between stocking rate and animal production, proposed by Wilson *et al.* (1984) and further developed by Wilson (1986), has not been applied and evaluated in full. It consists of 3 phases (Figure 1) and incorporates an earlier analysis by Jones and Sandland (1974). A description of each phase follows as this paper attempts to show that the relationship is robust and versatile, being suited to a wide range of pasture types and applicable to meat, milk and fibre production. Furthermore, it is proposed that the three linear components of the model, including possible transitions between Phases 3A and 3B, combine to mimic the various curvilinear relationships between animal production and stocking rate described by some workers (White, 1987; Heady and Child, 1994).

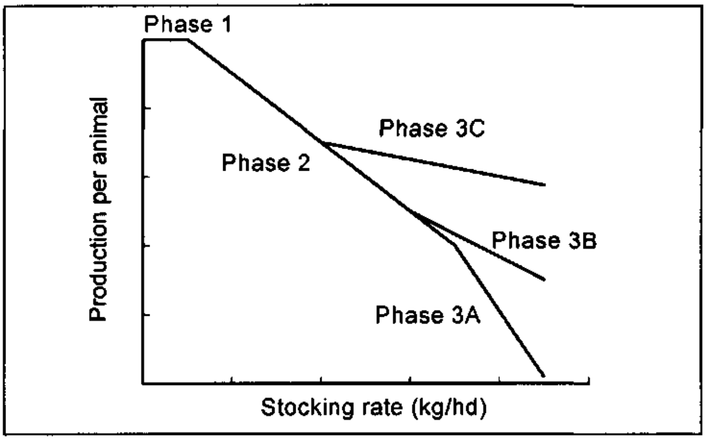

Figure 1. A stylised representation of the linear relationships between production per animal and stocking rate; developed from Wilson *et al.*, 1984. Explanations for each phase are contained in the text. The lines for Phase 3 illustrate different responses to changes in botanical composition and the relative magnitudes of the inflection points between Phase 2 and Phases 3A, 3B and 3C have no particular significance.

Phase 1 occurs at low stocking rates and is the potential animal production from a forage. It reflects the inherent quality of the forage, since forage supply is not limiting animal performance. Unless the forage is of exceptional high quality, the level of performance in Phase 1 will be less than the genetic potential of an animal for production. Evidence in support of Phase 1 is not readily available, since stocking rate experiments tend to operate in the other two phases of the relationship. However, experiments where animal production is similar across two or more relatively low stocking rates should demonstrate potential production. For example, milk production from tropical grass-legume pasture in north Queensland was similar for stocking rates of 1.3 and 1.6 cows/ha, thereby showing the potential production to be 3200 kg milk/cow/year, which increased to 3400 kg milk/cow/year when nitrogen improved the inherent quality of the pasture (Table 2). Similarly, at Lowmead in south east Queensland, average stocking rates of 0.62 and 0.82 steers/ha had no effect on liveweight gain from a Siratro pasture (Table 2).

The range of forage utilisation over which Phase 1 occurs, probably depends on the accessibility of quality herbage to a grazing animal and will vary across pasture types. In the GRASP simulation model of pasture and beef cattle production, Phase 1 is called potential liveweight gain (McKeon *et al.*, 1991) and it can be maintained while utilisation is less than 10% in tropical grass pastures.

Field measurements also show that Phase 1 is not constant across years, but varies in response to prevailing growing conditions. This common response is indicated by the coefficient of variation for animal performance across stocking rate treatments in long-term grazing trials (Table 2). Because of this year-by-year variation, the low stocking rates in some experiments may display a Phase 1 response in years of good pasture growth and a Phase 2 response in other years, as observed by Scattini (1973) and Jones *et al.* (1995).

Table 2. Examples of potential production (Phase 1) as indicated by the similar levels of production obtained at the two lowest stocking rates.

Milk production (kg/cow/yr); Source: Cowan and Stobbs, 1976.

Stocking rate (cows/ha)	1.3	1.6	1.9	2.5
Tropical grass + legume + 100 kg N/ha/yr	3387	3480	3028	3049
Tropical grass + legume, nil nitrogen	3236	3160	2785	2500

Liveweight gain (kg/steer in 314 days); Source: Bisset and Marlowe, 1974

Stocking rate (steers/ha)	0.62	0.82	1.24
Tropical grass + legume, nil nitrogen	183	183	173
Coefficient of variation (%)	14	11	15

Some reports (Stobbs, 1970; Roberts, 1980) suggest that, rather than being constant, animal production declines when stocking rates approach zero, since diet quality declines because of the accumulation of low quality herbage, or because legume growth is suppressed. Very low stocking rates are rarely used commercially, but if used, a decline in animal production probably will not occur because animals will maintain a quality diet through patch grazing or by diet selection across the landscape. Thus, Phase 1 is regarded as a useful concept that represents the upper limit of animal production from a pasture.

Phase 2 is a linear response that has been widely reported in literature (Walker, 1977; Roberts, 1980). It is described by a standard linear regression (Jones and Sandland, 1974):

$$\mathrm{P} = a + b\mathrm{SR} \qquad \text{Equation 1}$$

where P is performance per animal, SR is stocking rate (hd/ha), *b* is the slope of the line and *a* the intercept on the Y axis. As mentioned by White (1987), this linear model assumes the pasture is homogeneous, that the quantity of feed is proportional to the area of pasture, and that the relationship between animal production and feed available per animal approximates a regular hyperbola. In practice, as stocking rate increases animals compete for the most acceptable component of forage, which results in a decline in intake of digestible nutrients because the available forage is of lower quality and quantity. Within tropical pastures, animals prefer leaf to stem and green leaf to dead leaf (Stobbs, 1973; Chacon and Stobbs, 1976; Cowan *et al.*, 1986), and performance is dependent on the amount of green herbage ('t Mannetje, 1974, Walker *et al.*, 1987). Within temperate pastures there is not such a strong selection for leaf in preference to stem, and intake is dependent on the quality and quantity of standing pasture. Sward height is a useful indicator of forage quantity and intake (Hodgson, 1982, 1990). Furthermore, temperate species have, on average, a lower fibre content (about 10 units) and higher digestibility (about 15 units) than tropical species (Minson, 1980). Thus, animal performance from temperate pastures tends to exceed the performance from tropical pastures, but the processes that underpin Phase 2 of the stocking rate model apply to both types of pasture.

The literature shows the linear stocking rate model to be robust and versatile as it has been used in the following situations:

- beef cattle on rangeland (native vegetation including trees or shrubs): Shaw, 1978;
- beef cattle on native or naturalised vegetation augmented by a sown legume: Shaw, 1978; Partridge, 1986; Mears and Cullis, 1993;
- beef cattle or dairy cows on tropical grass pasture (one or more grass species usually sown into relatively fertile soil, often with regular applications of fertiliser): Cowan and Stobbs, 1976; Escuder, 1983; Davison *et al.*, 1985; Walker *et al.*, 1987; 't Mannetje and Jones, 1990; Jones *et al.*, 1995;
- beef cattle or dairy cows on tropical grass/legume pasture (one or more grasses sown with one or more legumes that may be of a tropical or temperate origin): Cowan *et al.*, 1975; Walker, 1977; Escuder, 1983; Compton *et al.*, 1989; 't Mannetje and Jones, 1990;
- sheep on temperate grass/legume pasture: Langlands and Bennett, 1973; Heerden and Tainton, 1989; and
- beef cattle on low-input temperate pasture: Neuteboom *et al.*, 1994.

Most of the above reports deal with beef cattle, where liveweight gain is directly dependent on the net energy available for growth in an animal. Hence, liveweight gain is not confounded by body reserves contributing to the level and quality of production, as may occur with milk from dairy cows or wool from sheep.

Moreover, the results of stocking rate experiments with dairy cows are often influenced by supplementary feeding to maintain production targets, whereas with beef cattle and sheep the low performing treatments are only fed supplements to avoid deaths. Also, there are few recent reports in the literature of stocking rate studies from the intensive farming systems in the northern hemisphere, probably because these production systems rely heavily on fodder conservation and supplementary feeding. For the above reasons, the subsequent discussion will mostly refer to stocking rate experiments with beef cattle in tropical and subtropical locations.

The intercept on the Y axis of the linear stocking rate model has no biological significance. The suggestion that it represents the potential for production at infinitely low stocking rate (Whiteman, 1980) is not valid, since Phase 1 demonstrates that concept. Rather, the magnitude of the intercept is influenced by both the magnitude of the slope and the overall productivity of a pasture. However, the magnitude of the slope of the linear stocking rate model indicates the rate of decline in production per animal as stocking rate increases. Experiments have shown that the slope of the stocking rate model:

- varies across grass species and pasture mixes within a location (Walker *et al.*, 1987; 't Mannetje and Jones, 1990), with smaller slopes (less negative) being associated with pastures that are relatively superior in quality;
- is reduced by applications of limiting soil nutrients such as nitrogen (Mears and Humphreys, 1974; Jones *et al.*, 1995) or phosphorus (Mears and Cullis, 1993) by increasing the supply and quality of forage, Table 3;
- varies across years in response to prevailing climatic conditions or to trends in soil fertility ('t Mannetje and Jones, 1990; Mears and Cullis, 1993; Jones *et al.*, 1995), Table 3; and
- varies between growing seasons (Bowen and Rickert, 1979; Cowan *et al.*, 1975; Walker *et al.*, 1987; Jones *et al.*, 1995), with relatively small slopes occurring in growing seasons when quality forage is readily available across all stocking rates; large slopes occur in seasons when pasture growth is restricted by cool temperatures or low rainfall and quality forage is in short supply relative to animal demand, Table 3.

In the four scenarios above, the magnitude of the slope during Phase 2 is dependent on the supply of quality forage in relation to animal demand. Hence the slope reflects the ability of the pasture to withstand heavy grazing. A grazing system with a large negative slope indicates that animal production is very sensitive to stocking rate changes and will need to be carefully managed to avoid degradation. The system is relatively fragile. Conversely, a grazing system with a small negative slope indicates that animal production is insensitive to stocking rate changes and a manager has a wide range of stocking rate options before degradation commences. The system is relatively robust and stable, possibly consisting of stoloniferous species that tolerate heavy grazing (Roberts, 1980). Since Phase 2 also covers the range of commercial stocking rates, its characteristics are vital to the economic analysis of a system as discussed in the next section.

Table 3. Examples of temporal variations in the slope of a Phase 2 response between liveweight gain per animal and stocking rate of steers grazing a tropical grass pasture that was fertilised with nil (N0) or 100 kg N/ha/year (N100); Source Jones *et al.*, 1995.

Time period	1973/74 -1975/76		1976/77 - 1978/79		1979/80 - 1981/82	
Fertiliser	N0	N100	N0	N100	N0	N100
Spring	-11	-11	-29	-18	-31	-21
Summer	-1	-1	-21	-5	4	5
Autumn	0	-8	7	2	-2	0
Winter	-10	0	-23	-11	-28	-8
All year	-22	-20	-65	-33	-57	-23

To better account for year-by-year variation, and provide a more general model for predicting animal production in Phase 2, liveweight gain has been related to various terms that combine the influence of stocking rate and prevailing environment, namely, annual rainfall and stocking rate as separate terms (Bransby 1985), annual rainfall divided by stocking rate (Gillard and Moneypenny, 1990), and a seasonal growth index for pasture divided by seasonal stocking rate (McKeon *et al.*, 1980; Rickert *et al.*, 1983). Whilst each new model extended the application of the linear stocking rate model, and simulated annual variation in animal production and financial returns, each model was restricted to a specific production system. The problem of specificity was partly overcome by a generalised model (McKeon and Rickert, 1984) that linked animal production to utilisation, a term that incorporates both the influence of stocking rate (expressed through intake) and prevailing climate (expressed through pasture growth). However, none of the above models adequately predicts the interaction between animal production, stocking rate and additional factors such as breed and age of animals (Robbins and Esdale, 1982; Laing *et al.*, 1984), compensatory liveweight gain, and diet selection across different land units in large paddocks (Stafford-Smith and Pickup, 1993).

Phase 3 represents the breakdown of the linear response of Phase 2 that occurs when the resilience of the pasture to grazing is exhausted and there is a shift in the botanical composition of the pasture that has an impact on animal production. A new response surface occurs, usually towards a more fragile system which is more sensitive to stocking rate (Phase 3A, Figure 1). However, in some situations the pasture composition changes towards a new system that is relatively insensitive to stocking rate (Phases 3B and 3C, Figure 1). Phase 3A represents pasture degradation typified by the loss of a preferred species, a reduction in basal area or an increase in weeds as previously mentioned. The point of inflection can be regarded as the maximum sustainable stocking rate of the system which corresponds to the 'peril point' in the description by Heady and Child (Figure 11-2, 1994). The situation with Phases 3B and 3C is not so clear because, although the system has degraded in one sense, it is less sensitive to stocking rate changes. Actual stocking rates will depend on a manager's attitude to change in botanical composition and the extra risk in using high stocking rates in a variable climate. These points are illustrated by the following examples.

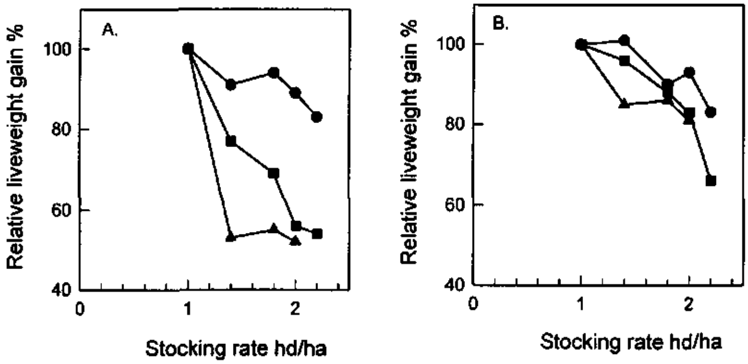

Figure 2. Examples of Phase 3A. Relative liveweight gain for steers grazing green panic (*Panicum maximum* var. *trichoglume*) at five stocking rates (1, 1.4, 1.8, 2, 2.2 hd/ha) on a fertile soil in south eastern Queensland; A. nil nitrogen fertiliser; B nitrogen fertiliser at 100 kg N/yr; ●, mean for years 1 and 2; ■, mean for years 6 and 7; ▲, mean for years 11 and 12. The constant for ●, ■,and ▲, (liveweight gain, kg/hd/yr) was 188, 197 and 144 in A and 199, 210 and 171 in B. The heavy stocking rate treatment was discontinued after 8 years because of pasture degradation. Data from McDonald *et al.*, 1995.

An example of degradation under high stocking rates (Phase 3A) is provided Jones *et al.* (1995), where weaner steers grazed green panic at 5 stocking rates and 2 rates of nitrogen fertiliser for 12 years (Figure 2). The sown grass component was largely replaced by weeds and unsown grasses at stocking rates above 1 steer/ha in unfertilised pastures, and above 1.8 steers/ha in fertilised pasture. Accordingly, the authors regarded these values to be the maximum sustainable stocking rate of the pastures. In another study, Orr *et al.* (1993) linked degradation to utilisation by showing that basal area and desirable species declined in Mulga woodland, while undesirable species increased, as utilisation increased (Table 4).

Table 4. Influence of four levels of utilisation over six years on the relative basal areas of perennial grasses in Mulga (*Acacia aneura*) woodland where, initially, the average total basal area was 2.3%; after Orr *et al.*, 1993.

Utilisation of annual growth (%)	20	35	50	80
Relative total basal area after 6 years	1.3	1.1	0.4	0.4
Relative basal area of *T. mitchelliana* * after 6 years	1.5	0.8	0.1	0
Relative basal area of *Aristida.* spp. * after 6 years	.6	2.5	.7	1.2

* *Thyridolepis mitchelliana* is a desirable species; *Aristida* spp. are undesirable.

They concluded that a maximum sustainable stocking rate was 0.2 sheep/ha or 0.03 AU/ha, because it gives rise to 20% utilisation (Table 1). Both examples clearly demonstrate that continued high utilisation leads to the symptoms of degradation mentioned previously. Two variations of the above response occur with heavy utilisation in grass/legume pastures. First, where legume cultivars are relatively unpalatable in the growing season compared with the companion grass, as occurs in stylo grass pastures, there is a dramatic reduction in the yield of perennial grass while the legume yield either increases or is relatively stable (Winter *et al.*, 1989). A loss in perennial grasses may be accompanied by an increase in annual grasses (Winks *et al.*, 1974) or perennial weeds (Rickert *et al.*, 1983). The second variation occurs when a legume is relatively palatable and there is a demise in legume relative to grass under high levels of utilisation. For example lucerne (*Medicago sativa*) is a highly palatable legume that will only persist in favourable environments under rotational grazing, and as a result, it is usually regarded as a short-lived perennial in the subtropics (Leach *et al.*, 1982; Lloyd *et al.*, 1991, 't Mannetje and Jones, 1990). Siratro (*Macroptilium atropurpureum*) is another pasture legume that declines under a high level of utilisation (Jones, 1979; Partridge, 1979; 't Mannetje and Jones, 1990) and productivity of the pasture declines as the legume disappears. In both cases plant pests and diseases may hasten the demise of the legume component.

An example of degradation that gives rise to a new production system that is less sensitive to stocking rate (Phase 3B) is provided by Jones (1992), who reported a decline in Setaria and Siratro and an increase in stoloniferous grasses (*Digitaria didactyla* and *Axonopus affinis*) through sustained heavy grazing. Similarly, commercial native pastures, originally dominated by the tussock-forming black spear grass (*Heteropogon contortus*), changed to near mono-specific swards of stoloniferous grasses, such as *Bothriochloa pertusa* or *Digitaria didactyla*, under heavy grazing (McIvor and Orr, 1991; Jones and Kerr, 1993). These examples display natural selection towards species that tolerate heavy grazing, provides such species exist in the original pasture or can invade. However, resting from grazing reverses the trend, provided the original species are still present as growing plants or in soil seed reserves (Jones, 1992). Thus, a Phase 3B response occurs when grass species that are edible and tolerant to heavy grazing replace the species lost through heavy grazing, and Phase 3A occurs when there is no such replacement.

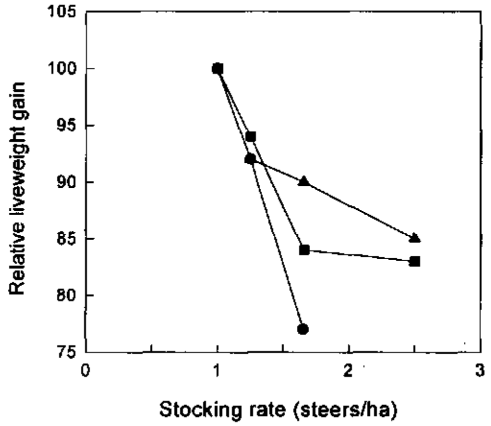

Figure 3. Example of Phase 3C. Changes in relative liveweight gain in response to 4 stocking rates (1.0, 1.25, 1.66, 2.5 steers/ha) over a 5 year period on a grass/legume pasture that originally consisted of Plicatulum (*Paspalum plicatulum*) and Setaria (*Setaria sphacelata* var. *sericea*) in combination with Siratro (*Macroptilium atropurpureum*) and Lotononis (*Lotononis bainesii*):- ● year 1; ■ year 3; ▲ year 5. Liveweight gains at 1.0 steers/ha were 178, 192 and 164 for years 1, 3 and 5 respectively. The pasture at the high stocking rate (2.5 steers/ha) was introduced in year 3 after being conditioned by heavy grazing. Data from Figure 6 of Compton *et al.*, 1989.

An example of degradation that gives rise to a new production system that is relatively productive and less sensitive to stocking rate (Phase 3C) is provided by data from Compton *et al.* (1989). Initially a sown grass legume pasture displayed the typical linear response to stocking rate (Figure 3). However, continued heavy utilisation led to a decline in sown grass and the legume Siratro, along with an increase in both the prostrate legume *Lotononis* and unsown stoloniferous grasses. This change in botanical composition was reflected in the progressive development of two distinct stocking rate responses, so that by year 5 the slope for the lowest two stocking rates was similar to year 1 and notably greater than the slope for the highest two stocking rates. Year 3 was a transition stage and the sustainable stocking rate was 1.25 steers/ha. Thus, a Phase 3C pasture differs from a Phase 3B pasture in that it contains both legume and grass species that tolerated heavy grazing, whereas the Phase 3B pasture does not have the legume present. As a result, the slope of Phase 3C response is likely to be smaller (less negative) than the slope of Phase 3B and the legume component may actually increase over a limited range of stocking rates. For example, doubling stocking rate from 3 to 6 steers/ha on *Brachiaria brizantha* alone reduced annual liveweight gain by 34% from 159 kg/hd, but with the legume *Arachis pintoi* included in the pasture, liveweight gain was reduced by only 13% from 178 kg/hd and the proportion of legume increased from 6.5 to 34% (Hernandez *et al.*, 1995). Clearly, unlike the Phase 3A examples with *Stylosanthes* mentioned above, both the grass and legume component are maintained under heavy grazing in a Phase 3C response.

Whether or not Phases 3B and 3C are regarded as resource degradation is open to question. Certainly stoloniferous grasses, alone or in combination with legumes that are tolerant to heavy grazing, can provide acceptable ground cover to minimise erosion. However, long-term measurements of animal performance in Phases 3B and 3C are not available, although early observations are encouraging (Jones and Kerr, 1993). Also, as stocking rate continues to increase, a Phase 3A response should eventually occur. Dramatic changes in pasture composition, such as the conversion from tussock to stoloniferous grassland, can also lead to conflicts between grazing managers and land administrators over the definition of grazing capacity (Abel, 1993; Scoones, 1993).

High stocking rates not only reduce production per animal, but also increase the variability of production (Rickert *et al.*, 1988). Results from a long-term grazing trial illustrate this point. The coefficient of variation (CV) of annual liveweight gain for the first 7 years of the experiment in Figure 2 increased from 5% to 58% as stocking rate increased from 1.0 to 2.2 steers/ha. Feed shortages occur more frequently with high stocking rates along with supplementary feeding or forced sales, the tactics normally used to counter the effects of drought. Also, relatively low animal performance means that cattle are retained longer to meet markets that require specific liveweights and the manager has fewer market options. Clearly, a high level of management is required with high stocking rates. This large interaction between animal performance, stocking rate and rainfall also influences the operation of computer models that simulate grazing systems. Simulations based on an 'average year', rather than historical records of climate, will give wrong stocking rate responses because the 'average year' ignores the effects of 'dry' years on the production system (McKeon *et al.*, 1986). The risks and the economics of using high stocking rates are discussed more fully in the next section.

Production per unit area

Since the linear Equation 1 describes Phase 2 of Figure 1, and production per unit area is the product of production per animal and stocking rate, a quadratic equation results:

$$\text{Pa} = a\text{SR} + b\text{SR}^2 \qquad \text{Equation 2}$$

where Pa is production per unit area and a and b are the coefficients of Equation 1 (Figure 4) (Jones and Sandland, 1974). Furthermore, the stocking rate at maximum Pa, given by $a/2b$, was called the optimum stocking rate because it is the biological optimum. Equation 2 is also a reasonable approximation of production per unit area in Phase 1, since the direct relationship between Pa and SR in Phase 1 closely resembles the left hand tail of the Equation 2. Thus, a quadratic relationship is a good representation of production per unit area for Phases 1 and 2. However, the discontinuity associated with the two Phase 3

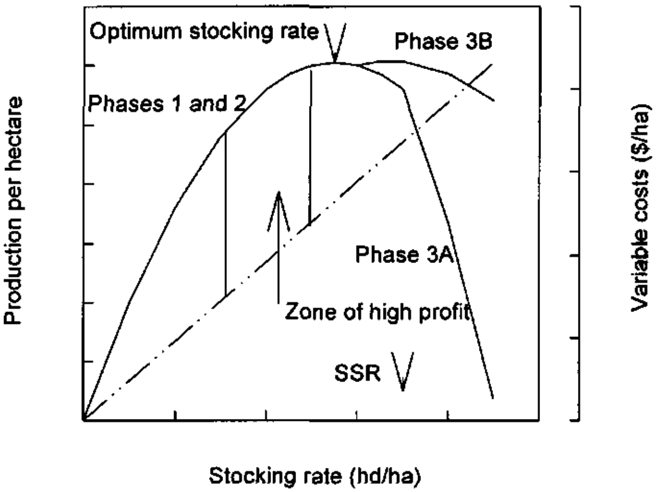

Figure 4. Data from Figure 1 expressed as production per unit area (Pa), the product of production per animal and stocking rate expressed as animal/ha (solid line). Variable costs (broken line) increase linearly with stocking rate. Maximum production per unit area, obtained at the optimum stocking rate according to Jones and Sandland (1974), will not occur in the zone of high profit. SSR is the maximum sustainable stocking rate for Phase 3A. Phase 3C is not shown.

responses gives rise to new response surfaces where Equation 2 does not apply (Figure 4).

If the value of each unit of animal production is known, Figure 4 can be expressed in economic terms where the Y axis becomes $/ha, the gross value of animal production. Further, if the value of each unit of animal production is independent of the level of production from individual animals, in other words constant for all stocking rates, then the $/ha response, with an appropriate scale on the Y axis, is identical to the response for animal production in Figure 4. In practice this assumption often does not apply, but it is a useful starting point for consideration of the interactions between stocking rates, economic returns and land degradation.

Variable costs ($/ha) for an enterprise include items such as cost of animals, fertiliser, commissions, transport, health costs, interest on money used to buy animals, etc. Whilst the components of variable costs might vary across enterprises, such costs increase with stocking rate and the difference between gross value and variable costs is a form of gross margin, an indication of operating profit (Figure 4). If some variable costs are only incurred at high stocking rates, such as costs for supplementary feeding, then total variable costs will increase in a curvilinear manner rather than the linear increase of Figure 4. Highest profit is obtained over a range of stocking rates where there is a large difference between the quadratic response of gross animal value and the linear response for variable costs.

The theoretical analysis of Figure 4 suggests that a manager has flexibility in the selection of profitable stocking rates, and that there is no economic incentive to use stocking rates that lead to degradation. Such a conclusion has a profound impact on farm sustainability and it needs to be tested against field results or other analyses of production systems.

Stocking rate and sustainable farming

Figure 4 implies that (i) the biological optimum stocking rate does not lead to pasture degradation because it is less than the maximum sustainable stocking rate, and (ii) maximum profit occurs over a range of stocking rates that are less than the optimum stocking rate and maximum sustainable stocking rate. Both issues are addressed below.

Biological optimum stocking rate and maximum sustainable stocking rate

Examination of the biological optimum stocking rate in relation to pasture degradation requires results from stocking rate experiments where some treatments led to degradation, while other treatments allow the biological optimum stocking rate to be determined from Equation 1. These conditions infer an experiment with a wide range of stocking rates conducted over a period of time that allows degradation to develop. Such experiments are rare, one being reported by Jones *et al.* (1995), where the maximum sustainable stocking rate for retaining green panic was 1 steer/ha in unfertilised pastures and 1.8 steers/ha in fertilised pasture. However, applying Equation 1 to the data generates a biological optimum stocking rate of about 2.0 and 4.0 steers/ha for the unfertilised and fertilised pastures, respectively, well above the observed maximum sustainable stocking rate. In an experiment over four years on a similar unfertilised pasture, Walker *et al.* (1987) obtained a biological optimum stocking rate of about 2.4 steers/ha, which exceeds maximum sustainable stocking rate from the long-term experiment by Jones *et al.*. Similarly, Mears and Cullis (1993) suggested that the biological optimum stocking rate was likely to be unsustainable for a white clover (*Trifolium repens*) and carpet grass (*Axonopus affinis*) pasture. The reason is not clear why these examples departed from the theoretical response in Figure 4, in that the observed maximum sustainable stocking rate was less than stocking rates for maximum production per unit area. However, a likely explanation is that the linear liveweight gain response is relatively insensitive to the undesirable changes in botanical composition, because it is based on results from several years, whereas the observed maximum sustainable stocking rate is based on a change in botanical composition which is caused by a specific combination of seasonal conditions and utilisation.

Another approach to estimating optimum and sustainable stocking rates is to conduct a stocking rate experiment with a management game that simulates pasture growth in relation to prevailing climate, animal production in relation to pasture utilisation, and cash flow in relation to prevailing costs and prices. Although a simplification of commercial systems, the model reflects the processes described above and is a useful tool for teaching principles of management (McKeon and Rickert, 1984). A stocking rates experiment was simulated on native pasture cleared of trees at Gayndah in south eastern Queensland (Figure 5). The linear regression of annual liveweight gain for 3-year old steers against stocking rate (SR), derived from the data points in Figure 5 was 178.7 - 313.7*SR (R^2 0.99; biological optimum stocking rate of 0.28 hd/ha). At the biological optimum stocking rate the utilisation was about 30%, a level that is likely to be ecologically sustainable in the long term, provided it is not exceeded in 30% of years (McKeon *et al.*, 1991). Thus, the biological optimum stocking is similar to the maximum sustainable stocking rate for the pasture and the example provides a reasonable demonstration of theoretical response in Figure 4. However, the annual liveweight gain was only 69 kg/hd/yr, a level of production that leads to unacceptably old turnoff, and therefore is economically unsustainable.

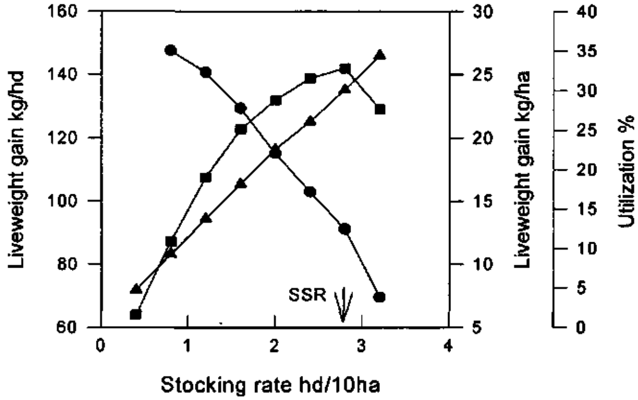

Figure 5. Influence of stocking rate on liveweight gain per head, ●; liveweight gain per hectare, ■ ; and pasture utilisation, ▲. Average performance over 14 years for 3-year old steers grazing native pasture cleared of trees at Gayndah, south-eastern Queensland. Data obtained from the BEEFUP model (Rickert *et al.*, 1990). Each year the cattle entered the system in winter at 400 kg liveweight and remained for 12 months. Maximum liveweight gain per hectare occurred at a stocking rate of 0.28 hd/ha and a critical level of utilisation (30%) for long term sustainability. However, stocking rates exceeding 0.24 hd/ha led to forced sales and the system was unsustainable economically (Figure 6).

Whilst the above analyses are inconclusive and somewhat conflicting, they suggest that reference to the stocking rate that results in maximum animal production per hectare as the biological optimum stocking rate is unwise. Such a stocking rate is likely to be impractical because it leads to pasture degradation in the long-term and/or because the resulting low and variable level of production per animal is likely to have negative impacts on quality of animal product, farm economics, and animal welfare. Furthermore, stocking rates that give maximum production per unit area should not be emphasised when analysing stocking rate responses. Rather, emphasis should be given to the stocking rate that is the maximum sustainable stocking rate of the pasture.

Profitability

It is evident from Figures 1 and 4 that the most profitable stocking rate must be greater than the stocking rate giving maximum value per animal, unless variable costs are so high as to give zero gross margins. On the other hand, the most profitable stocking rate must be less than the stocking rate for maximum value per unit area, unless variable costs are zero (Workman and Fowler, 1986; Holmes, 1988). Thus, the zone of high profit in Figure 4 is to be expected, but it will occur at lower stocking rates as variable costs increase, and higher stocking rates as variable costs decrease, relative to the gross value of production. Therefore, the convention used by a farmer in calculating variable costs has an influence on the stocking rate for highest profit. Also, the stocking rate for highest profit, relative to the maximum sustainable stocking rate of the pasture, indicates the likelihood of profit maximisation contributing to pasture degradation. Profitability is also affected by interactions between stocking rates and both market prices and a farmer's attitude to risk, as explained below.

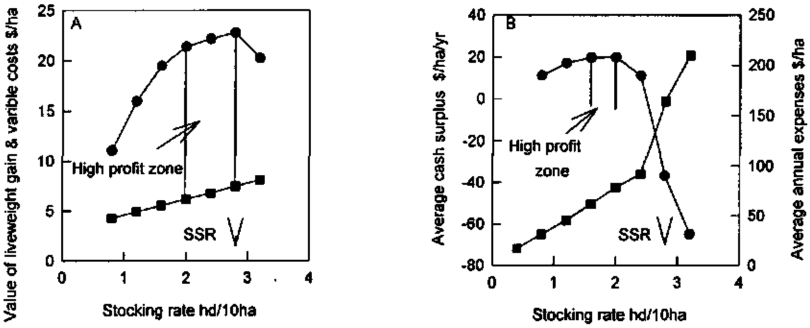

Figure 6. Average financial performance over 14 years from 3-year old steers grazing native pasture cleared of trees at Gayndah, south-eastern Queensland. Data obtained from the BEEFUP model (Rickert *et al.*, 1990) using inputs of historical rainfall and actual prices adjusted to a common base. Each year the cattle entered the system in winter at 400 kg liveweight and remained for 12 months. SSR is the maximum sustainable stocking rate (30% utilisation, Figure 5). (A). Influence of stocking rate on value of liveweight gain, ●; and variable costs associated with grazing (not purchasing) the cattle, ■. (B). Influence of stocking rate on annual cash surplus, ●, and expenses in purchasing and grazing the cattle and servicing debt (17.5% pa.), ■. Highest profit occurred over a range of stocking rates that were less than SSR and were further reduced by a more comprehensive analysis of Figure 6B.

Simulation studies for a beef enterprise (Figure 6A) support the theoretical pattern in Figure 4 where the stocking rates with highest profit (value of liveweight gain less costs incurred in grazing) are less than the stocking rate giving maximum production per hectare, and less than the stocking rates that lead to pasture degradation in the long term. However, when cash flow is considered, which includes the cost of buying cattle and servicing accrued debt (Figure 6B), the systems 'crashes' drastically at stocking rates above the sustainable level because of low production, debt servicing charges and forced sales. Further, the most profitable stocking rates are lower than the most profitable stocking rates in the simple economic analysis of Figure 6A. The above example highlights the role of economic convention in determining the likelihood of profit maximisation stimulating degradation. For example, managers who place no value on farm-bred animals until sale, or disregard the cost of family labour, are likely to perceive lower variable costs, and regard higher stocking rate as profitable, than a livestock trader who borrows money to buy cattle for fattening. Another, more extreme, unconventional economic analysis applies when the farmer's goal is to maximise animal numbers with little regard for marketing a quality product (Abel, 1993; Scoones, 1993; Simaraks, 1993).

Neither Figure 4 nor 6 indicates interactions between stocking rate and quality or price of animal products, and the impact they might have on the most profitable stocking rate. In practice, the sale price for beef cattle tends to increase as stocking rate decreases, because the quality of carcasses improves (Hamilton, 1975; Jones *et al.*, 1995), thereby maximising profit at lower stocking rates than would occur if prices were constant across stocking rates. Field studies also support the conclusion that maximum profits occur at moderate stocking rates. For example, Hamilton (1975) found that the maximum gross margins occurred at a stocking rate that resulted in a high proportion of first-grade carcasses. Similarly, Holechek *et al.* (1995, Table 8.5) reviewed results from 15 stocking rate trials on rangeland and concluded that the most profitable stocking rates resulted in sustainable levels of forage utilisation. Whilst these reports suggest that long-term profit maximisation is not a major factor influencing land degradation in extensive beef production systems, other factors, such as fluctuations in cattle prices, value of land, and the attitudes and perceptions of individual managers, strongly influence farm stocking rates (Holmes, 1988; Danckwert and Maris, 1989).

The picture is more complicated with sheep or goats because their products may include both fibre and meat. Also, in contrast to beef production, the sale price of fibre may increase with increasing stocking rate since fibre diameter decreases, thereby compensating for a decline in fibre production per animal (White and McConchie, 1976). In a simulation experiment on wool production, this interaction increased the stocking rate for maximum profit by 12% (White and Morley, 1977). Clearly, there is a tendency for the zone of highest profit to occur at higher stocking rates, closer to those that lead to pasture degradation. For example, with lamb and wool production, the most profitable stocking rate was higher than the most profitable stocking rate for beef production, being the highest stocking rate that did not require supplementary feeding (Hamilton, 1975). For the extensive production systems of Queensland, studies on wool production in relation to pasture utilisation, and results from farm surveys, both suggest that the most profitable stocking rates are similar to farm carrying capacity (Beale *et al.*, 1986). Government policies that have linked price support schemes to better fibre quality (Taylor, 1990), or created relatively small farms (Mills *et al.*, 1989;

MacLeod, 1990), have encouraged pasture degradation. Thus, profit maximisation is more likely to be a factor that contributes to pasture degradation with fibre production, since the interaction between stocking rate, profit and pasture degradation seems to be more acute than with extensive beef production. In addition, because of different grazing behaviours in drought conditions, sheep are more likely to damage vegetation than cattle (Wilson, 1986).

In intensive production systems using sown pastures, economic stocking rates can be determined from knowledge of expected herbage production, safe levels of herbage utilisation, and the forage requirements of different animal classes, taking into account requirements for fodder conservation and the feeding of supplements (Hodgson, 1990). Outputs and costs of inputs can be optimised (Doyle, 1987), and conveniently calculated by decision support packages that estimate least-cost rations for specific production targets (Hulme *et al.*, 1986; McCall and Sheath, 1993). Such analyses clearly show an optimum stocking rate for maximum profit that should be sustainable (Doyle and Lazenby, 1984). Of course, unfavourable conditions may lead to pasture degradation, but rejuvenation by reseeding is usually possible provided soil erosion is controlled. Thus, interactions between stocking rate, profit and land degradation in intensive production systems, compared to extensive systems, are characterised by less variation in climate, forages that are relatively uniform in botanical composition and constant in quality, and a wider range of management options available to the farmer (Heitschmidt, 1993).

The above discussion highlights the roles of economic convention and market forces in determining the likelihood of profit maximisation stimulating degradation, but attitude of the farmer to risk is also important. All managers of grazing systems operate in an uncertain world because of uncontrolled variation in weather, costs and prices. In such an environment maximising profit may not be the only management goal because of the associated risks. One approach to the expression of risk is probability distributions of key outputs (e.g. gross margin) from simulation experiments that allow a manager to balance the benefits of a management option, such as higher stocking rates, against the extra uncertainty this might bring (Bransby, 1985; Rickert and McKeon, 1985; McKeon *et al.*, 1986). Another approach is to incorporate an individual's attitude to the risk with different management options in a 'utility function' that expresses relative satisfaction with the financial outcomes (MacArthur and Dillon, 1971; White and Morley, 1977; Doyle, 1987). Because of the risk factor associated with high stocking rates on dairy farms in England and Wales, farm profit was significantly less than maximum profit (Doyle and Lazenby, 1984), thereby suggesting that the attitude to risk among farmers will lead to conservative stocking rates. However, Holmes (1988) believes a farmer's attitude to risk changes with economic times and the greater risk associated with high stocking rates becomes more acceptable in depressed economic times. It therefore follows that degradation is more likely in a grazing industry with small profit margins or narrow terms of trade.

It should not be forgotten that successful farming involves much more than selecting correct stocking rates. Frequently, a manager attempts to integrate different forage types into a feeding regime that covers two or three years of grazing, while coping with a host of issues related to farm and financial management. More refined economic analyses are more appropriate than the simple gross margin analyses used above (Berton and Bryan, 1983). When capital is limited, as is the case during farm development, it is preferable to maximise returns on additional money invested rather than gross margin per hectare (Wicksteed and Jamieson, 1986). Thus, the internal rate of return on increasing stocking rates needs to be compared against the returns for alternative strategies.

Practical experiences

Hitherto, the 3-Phase linear model of animal production and stocking has been supported by research results, and practical conclusions from the model, such as moderate stocking rates are likely to be most profitable, have not been confirmed by farmer experience. The role and importance of farmer experiences in providing insight for research (Walker, 1991) is occasionally acknowledged by inviting farmers to describe their grazing systems at technical conferences, such as the descriptions for different grazing systems in Table 5. Stocking rate was an important management option in five grazing systems ranging from extensive tropical rangeland to intensive temperate grassland. Each farmer attempted to have periods of high forage demand, such as calving or lambing, coincide with periods of active pasture growth. However, the intensive grassland farmers from New Zealand described stocking rates with little consideration of year-by-year variation in forage supply, presumably because of a reliable rainfall and infrequent droughts. In contrast, the farmers from rangeland in northern Australia and South Africa advocated low stocking rates and flexible management strategies to accommodate wide year-by-year variation in rainfall. The ley farming system from southern Australia used crop residues and conserved fodder to alleviate drought. Together these reports support the view expressed earlier, namely, maximum sustainable stocking rates in a reliable climate can be estimated from knowledge of forage growth and animal requirements, whereas maximum sustainable stocking rates in extensive grazing systems must take account of wide year-by-year variation in rainfall. For this reason, additional consideration is now given to farmer experiences and the application of conclusions from the foregoing discussion in extensive grazing systems in variable climates.

Table 5. Management of stocking rate in grazing systems of increasing intensification. A selection from the producer forums at the XVII International Grassland Congress.

Grazing system	Management strategies	Source and stocking rate
Rangeland: beef cattle, goats and wildlife on arid sweet bushveld of northern Transvaal, South Africa	Use low stocking rates and adapted cattle; sell to reduce stocking rates early in a drought; control type and number of wildlife.	Ivy *et al.*, 1993. 11 ha/LSU (0.091 AU/ha)*
Rangeland: beef cattle on native pastures in eucalypt woodland in northern Queensland, Australia	Use low stocking rates and adapted cattle; progressively sell cattle as drought develops; flexibility in all aspects of management.	Mann, 1993. 8.13 ha/hd (0.118 AU/ha)*
Ley farming: grain and wool from dryland crops and grass clover pastures in south western New South Wales, Australia	Stocking rates vary with annual cycle of feed supply; crop residues used to spell pastures; fodder conserved for drought.	Hutchings, 1993. 22.5 - 3 dse/ha (3.7 -.5 AU/ha)*
Grassland: sheep and beef cattle on grass clover pastures in hill country of North Island of New Zealand.	Stocking rates vary with annual cycle of feed supply; many paddocks and high level of grazing management; normal rotational grazing adjusted to alleviate drought.	Neeley and Parminter, 1993. 10.5 su/ha. (1.75 AU/ha)*
Grassland and crops: grass clover pastures and silage crops for all-year milk production in New Zealand.	Year-round forage supply matches demand which is controlled through stocking rate and calving time; irrigated pasture to alleviate drought.	Guy, 1993. 3.9 cows/ha (5.4 AU/ha)*

* Equivalent stocking rate expressed as Animal Units - a 500 kg non-lactating cow.

Variability of climate is acknowledged in the definition of maximum sustainable stocking rate, a stocking rate that does not exceed a critical level of utilisation in the majority of years (e.g. 70%). Thus, ecological damage from overutilisation, that might occur in some dry years, is alleviated by low levels of utilisation and rehabilitation in wet years. However, successful farmers are usually not accustomed to such an objective definition of maximum sustainable stocking rate. Instead, they rely on past experiences and observations on the relative abundance of desirable and undesirable species to determine maximum sustainable stocking rates, and regulate stocking rate, fire and grazing management to maintain a desirable botanical composition (e.g. Ivy *et al.*, 1993; Mann, 1993). Perhaps farm managers would routinely link pasture utilisation with stocking rates if utilisation was better understood and readily estimated for each paddock on a farm by a computer model or decision support system (Scanlan *et al.*, 1994). Another objective and practical indicator of desirable botanical composition and maximum sustainable stocking rates might be the suggestions by Tothill and Gillies (1993) for native pasture, and Jones *et al.* (1993) for sown grass pasture, that desirable species should be greater than 70% of total botanical composition. Alternatively, maintaining minimum levels of plant residue is a simple management strategy for sustainability in rangelands of Texas and California as previously mentioned (Heady and Child, 1994). Whilst practical indicators of sustainability of grazing systems need to be better defined, and might vary across environments and types of pasture, one essential attribute is clearly evident. Ecological sustainability will require farm managers to have a commitment to goals in botanical composition, as well as animal production.

Some farmers hold the view that reducing stocking rate by selling animals as a drought develops in grazing systems based on perennial pastures is a better option economically than maintaining animal numbers through supplementary feeding (Karuah, 1992; Mann, 1993). Whilst the economic benefits of a selling strategy will depend on the duration of the drought, the cost of drought feeding, and the relative cost of replacement stock, such a strategy is likely to be much better ecologically than supplementary feeding. Lower stocking rates with a drought selling strategy should foster seedling recruitment when the drought breaks, a vital process in pasture rehabilitation and maintaining desirable botanical composition in perennial pastures (Orr *et al.*, 1991; Orr and Paton, 1993).

Finally, and perhaps most importantly, it is encouraging to see reports from separate farmers (Ivy *et al.*, 1993; Mann, 1993; Purvis, 1987) supporting a basic contention of this paper that modest stocking rates lead to both ecological and economic sustainability in extensive grazing systems. Thus, theoretical analyses, research results and farmer experience all support a principle that is not well acknowledged in grazing industries.

Expectations of society

The world is a global village which is interested not only in primary outputs from grazing systems (e.g. reliable supplies of high quality meat, milk and fibre at affordable prices), but also secondary outputs that have an impact on the wider community. Indeed, there is a trend for governments to demand standards of management in grazing systems that help to sustain the environment and lifestyle experienced by the wider community. This paper will not review the nature and objectives of government demands, but instead will illustrate the trend by briefly referring to two secondary outputs from grazing systems that are directly affected by stocking rate.

Contemporary society requires reliable supplies of **fresh water**, which are stored in reservoirs that often collect runoff water from grassland, or are drawn from aquifers recharged by deep drainage from grassland. The interaction between utilisation, runoff and soil erosion at a farm level has already been mentioned, but on a catchment scale, over-grazing and high levels of sediment in runoff water can significantly reduce the effective life of a storage reservoir. For example, public concern over siltation and water quality in a large dam on the Burdekin River in northern Australia arises from overgrazing and land degradation in its catchment (McKeon *et al.*, 1991). Likewise, overgrazing that increases runoff and bush encroachment on the Edwards Plateaux of Texas significantly reduces the recharge of an aquifer that is the water supply for the city of San Antonio, and as a result, urban demands are influencing farming practices (Thurow and Taylor, 1995). Both examples illustrate an emerging trend. As cities expand and their demand for fresh water grows, so too will society's demand for water supplies from grassland. Managers will be obliged to respond to the future demands.

Another emerging expectation of contemporary society is that grassland, and farm managers, should play a significant role in reducing the concentration of **greenhouse gases** in the atmosphere which appear to be changing the world's climate (Pittock, 1993). Whilst this is a complex issue that is currently not well understood, the grasslands of the world influence the concentration of greenhouse gases by being a sink that restricts the increase in carbon dioxide concentration from other sources; by being a source of methane, much of which is emitted by the cattle population of the world; and by releasing nitrous oxide, particularly from urine patches and soils receiving nitrogen fertiliser or manure (Minami *et al.*, 1993). Management options that have an impact on the above processes are being investigated in both extensive and intensive grazing systems. In extensive grazing systems, Howden *et al.* (1994) showed that a reduction in stocking rate would lead to a significant reduction in methane production and to an improvement in land condition, but the response was dependent on the likely pattern of climate change. In intensive grazing systems, evidence suggests that less intensive farming practices (lower stocking rates, less nitrogen fertiliser, more grass/legume pastures) will lead to large reductions in emissions of carbon dioxide, methane and nitrous oxide (Bakken *et al.*, 1994; Weissbach and Ernst, 1994). Whilst these two studies both suggest that lower stocking rates will be an important factor in reducing global emissions of greenhouse gases, it is also clear that the carbon, nutrient and energy balances of farming systems need to be better understood. In this regard, experimental farms which demonstrate farming practices that reduce greenhouse gas emissions while being economically viable, provide a holistic base for scientific studies and guidance for farmers and politicians (Aarts *et al.*, 1994). Certainly, sound advice on sustainable grazing systems is sorely needed as it has been argued by Rifkin (1992) that a dramatic reduction of the world's cattle population (stocking rate of the world) is warranted because of methane emissions, land degradation and inefficient use of grain in feedlots. As the saga on greenhouse gases and climate change unfolds, the wise response by grazing industries for sustainability in ecological, economic and political terms, might be the advice from Stafford-Smith and Foran (1993), who argue that sound financial management and marketing need to be accompanied by a shared long-term vision, and adoption of high environmental standards in production and processing.

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Leguminous forage shrubs for acid soils in the tropics

R. Schultze-Kraft

Institute of Plant Production in the Tropics and Subtropics
University of Hohenheim (380), D-70593 Stuttgart, Germany

Abstract

The dual-purpose function (livestock feed and soil improvement) of tropical forage legumes in general is highlighted. Forage shrubs and trees that offer the advantage of additional purposes (fuelwood and others) are most useful for smallholder production systems and are suggested to have a higher potential to persist under grazing than herbaceous plants. The most widely used species, *Leucaena leucocephala* and *Gliricidia sepium*, however, are not adapted to the very acid, highly Al-saturated Oxisols and Ultisols that cover vast areas of the subhumid and humid tropics. Evaluation within the forage genetic resources collection kept at CIAT, Colombia, has shown that several, relatively unknown species grow well on such soils: *Flemingia macrophylla*, *Cratylia argentea*, a still undescribed *Calliandra* species, *Desmodium velutinum, Tadehagi triquetrum*, and *Codariocalyx gyroides*. Although their yield potential is considerably lower than that of the trees *Leucaena* or *Gliricidia* on non-acid soils, some agronomic characteristics of these species such as drought resistance, tolerance to insect pests and diseases, leafiness, and regrowth potential, are outstanding. However, the forage value of most species is severely constrained by high contents of condensed tannins that are associated with digestibilities as low as 20% and lack of acceptability by grazing livestock, mainly during the rainy season. *Cratylia argentea* and *Desmodium velutinum*, in part also *Codariocalyx gyroides*, are exceptions and warrant further research for their possible use in the humid tropics (*C. argentea*, *C. gyroides*) and subhumid tropics (*C. argentea*, *D. velutinum*). The chances for adoption of cut-and-carry forage technologies based on relatively low-yielding species are discussed and a series of research topics is suggested.

Role of tropical forage legumes

Forage legumes have the potential to play a significant role in sustainable agricultural production systems in the tropics (e.g., Humphreys, 1994). Tropical forage legumes should be regarded as dual-purpose plants as they are not only able to provide highly nutritious feed to livestock, but also to contribute to soil conservation and improvement. The most important characteristics are the ability to fix atmospheric nitrogen – if and when there is an effective symbiosis with (*Brady*)*rhizobium* –, the high crude protein content in aerial biomass, and, in many cases, a deep-reaching tap root system leading to drought avoidance and nutrient pumping and cycling.

Subsequently, and depending on associated species and grazing management, substantial livestock production increases can be achieved through the introduction of a legume into grass-only pastures, both native grasslands and improved pastures, or through supplementing livestock on a grass-only pasture with access to a legume-only paddock. The legume effect is in the seasonally dry tropics particularly strong during the dry season (Table 1).

Table 1. Effect of tropical forage legumes on livestock performance (in kg per animal per year or g per animal per day).

Pasture type, location	Legume species	Livestock performance without legume	with legume	Reference
Native (*Heteropogon contortus*), dry subtropics, central Queensland, Australia	*Stylosanthes humilis*	83 (kg/an/yr)	121 (kg/an/yr)	Shaw and 't Mannetje (1970)
Improved (*Brachiara brizantha*), humid tropics, Costa Rica	*Arachis pintoi*	119 (kg/an/yr)	154 (kg/an/yr)	Hernández *et al.* (1995)
Native, dry tropics, Northern Territory, Australia	*Centrosema pascuorum**	-183 (g/an/day*)	+489 (g/an/day*)	McCown *et al.* (1986)

* Supplementation as ley during main dry season

Similarly, in integrated production systems such as ley-farming where forage legumes are combined with crops, there can be a substantial impact on soil fertility and soil structure (Rao *et al.*, 1992), and thus on subsequent crop yields (Table 2). The soil-improving effect of a previous legume crop is likely to be particularly strong on low-fertility soils. Additional important functions of legumes – but also of grasses – can be, among others, soil cover and erosion control (in the case of species with appropriate growth habits), and the break of pest cycles (Humphreys, 1994).

Table 2. Effect of tropical forage legumes on subsequent crop yields in integrated production systems.

Legume species	Location; duration	Crop	Crop yield (kg/ha) without	with previous legume	Reference
Pueraria phaseoloides (in grass* pasture)	Colombia, Llanos Orientales; 10 years	Rainfed rice	1360	3070	CIAT (1990)
Stylosanthes hamata (fodder bank)	Northern Nigeria; 3 years	Maize	1275	2507	Mohamed-Saleem *et al.* (1986)
Stylosanthes guianensis (improved fallow)	SW Nigeria; 1 year	Maize	2000	4750	L. Muhr and R. Schultze-Kraft (1996 unpubl.)

* *Brachiaria decumbens*

Forage shrubs and trees

Although research and development of tropical forage legumes has been substantial during the past 40 years, technology adoption and impact at the commercial level has in most countries been limited. One of the reasons is the lack of persistence of legumes under grazing. A number of reasons can be responsible for this, among them mismanagement and lack of appropriate, plant morphology related, persistence mechanisms ('t Mannetje, 1991).

Leguminous shrubs and trees offer a series of potential advantages over herbaceous species in grazing systems, as part of their growing points might be unaffected by livestock because they are out of their reach, and as their stems and branches might be less sensitive to physical damage by trampling. Furthermore, they might grow out of competition for light by the associated vegetation. Additional advantages as forage plants are, potentially, higher yields per unit area and the capacity to retain high-quality forage under moisture stress conditions. Finally, depending on their size, shrubs and trees may play a very significant role in the production system as multi-purpose plants by additionally providing erosion control, fuelwood, shade, mulch material etc., and by soil improvement through nutrient cycling (Withington *et al.*, 1988; Catchpoole and Blair, 1990). Leguminous shrubs seem to fit especially well into smallholder systems where crop production is often combined with livestock production based on cut-and-carry forage. The increasing attention that tropical forage shrubs and trees have been receiving lately by scientists is reflected by the number of books and workshop proceedings published during the past decade (Withington *et al.*, 1988; Devendra, 1990; Speedy and Pugliese, 1992; Gutteridge and Shelton, 1994).

The best-known leguminous forage shrub species are *Leucaena leucocephala* and *Gliricidia sepium*. Both are widely used and well researched, and there is a vast amount of information available on their production potential and actual performance under a wide range of agroecological and production systems conditions (e.g., NRC, 1984 and NFTA, 1980-1992 for *Leucaena* spp.; Withington *et al.*, 1987 for *G. sepium*). However, there are hardly any reports – with occasional exceptions such as in Szott *et al.* (1991) for *G. sepium* – which suggest that in *L. leucocephala* or *G. sepium* there is germplasm adapted to the acid and highly aluminium saturated soils characteristic for vast Ultisol and Oxisol areas in the tropics.

The acid-soil problem

Acid soils of low natural fertility cover considerable areas in tropical America, Africa, and Southeast Asia. It is estimated that, for example, in the central lowlands of tropical South America alone and in Africa, there are about one billion hectares of Oxisols and Ultisols (Sanchez and Salinas, 1981). The agricultural potential of such soils is often severely constrained, because pH values lower than 5.3-5.5 are normally associated with high levels of exchangeable aluminium. When these levels reach 70% saturation of the effective cation exchange capacity in the top soil, the soil is usually considered as Al-toxic and, unless amended with high lime doses, not suitable for most crops (Cochrane *et al.*, 1980).

In addition to high Al levels, soil acidity is often associated with other factors which contribute to a general infertility complex. Such factors are low cation exchange capacity, low contents of exchangeable bases and available phosphorus (often associated with high P-fixing capacity), toxic manganese contents, low contents of organic matter, and deficiencies of sulfur and some micronutrients (Cochrane *et al.*, 1980). As the effect of these factors is often masked by that of high Al saturation, and vice versa, the term "acid, infertile soils" or "acid, low-fertility soils" is often used in literature when plant growth on Oxisols and Ultisols is discussed (e.g., Evans and Szott, 1995).

These acid, highly Al-saturated soils, together with eroded, degraded soils, form part of those marginal lands where crop production might not be feasible economically and where extensive livestock production is often the only possible form of land use. In these areas of the subhumid and humid tropics pasture production will play an increasing role, thus releasing fertile soils for crops (Schultze-Kraft *et al.*, 1993). The need for continuing research to develop legume-based, soil fertility restoring technologies for sustainable agricultural production systems on such acid soils is increasingly recognised (e.g., Szott *et al.*, 1991). Among others, this concern led, for example, to a recent state-of-the-art workshop on nitrogen fixing trees for acid soils, organised by the Nitrogen Fixing Tree Association (NFTA) and the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) in Costa Rica (Evans and Szott, 1995).

Evaluation of shrub species

Within the development of improved-pasture technology for acid, infertile tropical soils, a comprehensive germplasm collection was gathered in the 1970's and 1980's by the Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. There are now about 18,000 accessions of a wide range of legume species available (Schultze-Kraft *et al.*, 1993), many of them with potential adaptation to Oxisols and Ultisols. About 1200 accessions belong to species that are classified as trees and shrubs (Lascano *et al.*, 1993). In this context, however, attention needs to be drawn to difficulties, due to intraspecific variability, in the objective classification of life form and growth habit at the species level. For example, in *Stylosanthes scabra*, a species that is commonly regarded as a fairly low-growing subshrub, there are very woody ecotypes growing as high as 2 m, whereas, for example, in *Desmanthus virgatus*, which is commonly classified as a shrub species, perfectly prostrate forms can occur.

A first attempt to identify within the CIAT collection tree and shrub legumes that are adapted to acid, low-fertility soils was conducted in Colombia in 1988/89 by comparing the performance of 23 species on a low-fertility, acid (pH 4.0) and highly Al-saturated (91 %) Ultisol at Santander de Quilichao with that on a fertile, slightly alkaline Vertisol (pH 7.5) at Palmira. Species tested were *Acacia angustissima, A. farnesiana, Albizia lebbeck, Cajanus cajan, Calliandra calothyrsus, Calliandra* sp.n. (a new species closely related to *C. calothyrsus*), *Clitoria fairchildiana, Codariocalyx gyroides, Cratylia argentea, Dendrolobium triangulare, D. umbellatum, Desmanthus virgatus, Desmodium velutinum, Erythrina fusca, E. poeppigiana, Flemingia macrophylla, Leucaena diversifolia, Phyllodium longipes, P. pulchellum, Schizolobium parahyba,* and *Sesbania sesban*. Control species were *Leucaena leucocephala* and *Gliricidia sepium*. As result, on the fertile Vertisol the highest foliage yields were recorded for *L. leucocephala, Acacia angustissima* and *Sesbania sesban,* whereas on the very acid, low-fertility Ultisol *Flemingia macrophylla, Cratylia argentea* and *Calliandra* sp.n., though in part considerably lower-yielding than on the Vertisol, were by far the most productive species (Table 3).

Table 3. Cumulative dry matter yields (g/plant in three 3-monthly cuts) of tropical shrub legumes on two contrasting soils in Colombia (R. Schultze-Kraft and P. Perdomo, unpubl.).

Species	Ultisol pH (H_2O) 4.0, 90% Al sat.; 5.7 % OM	Vertisol pH (H_2O) 7.5, 0% Al sat.; 2.6 % OM
Calliandra sp.n.	348	2906
Cratylia argentea	309	454
Flemingia macrophylla	478	1406
Gliricidia sepium	4	3667
Leucaena leucocephala	3	8822
18 remaining spp. (range)	0.3-140	19-6789
LSD (5%)	81	810

Best intermediate species (Ultisol): *Cajanus cajan, Calliandra calothyrsus, Codariocalyx gyroides, Clitoria fairchildiana, Desmodium velutinum, Phyllodium* spp.

As there was preliminary evidence that some of the better-adapted species were not readily consumed by cattle, two small-plot cafeteria grazing trials were conducted at the same Ultisol site including some selected shrub legumes in pure stands (Schultze-Kraft *et al.*, 1989). At another site, Carimagua, Colombian Llanos Orientales, a small-plot grazing trial was conducted on an acid (pH 4.9), low-fertility and highly Al-saturated (86 %) Oxisol, also with some selected shrub legumes that were sown into native, low-quality *Trachypogon* savanna (Thomas and Schultze-Kraft, 1990). Plants grew quite well at both sites, but there was a marked variation between seasons in legume consumption: during the dry season the acceptability of most shrub legumes by grazing cattle was in general high, but it was quite low during the wet season. Low acceptability was associated with low digestibility. Of the species that were common to the trials at both sites, particularly *Flemingia macrophylla, Desmodium strigillosum* (a subshrub), *D. velutinum* and *Tadehagi triquetrum* (another subshrub) were considered to have a good potential, although forage acceptability and digestibility of *F. macrophylla* and *T. triquetrum* were particularly low. *Cratylia argentea* was not included in these small-plot grazing trials.

In subsequent years, shrub legume evaluation for acid, low-fertility soils in tropical America was extended from the subhumid climate to the humid tropics, e.g., in Peru and Bolivia. As a result, *Calliandra* sp.n., *Codariocalyx gyroides, Cratylia argentea* and *Flemingia macrophylla* are considered to have a high agronomic potential on the Ultisols and Inceptisols where they were tested (CIAT, 1991; Vallejos and Cardona, 1995).

Promising species and constraints

Concluding from the experiences in forage shrub evaluation to date, there are several species that can be regarded as well adapted to those particularly acid and highly Al saturated Oxisols and Ultisols that prevail in tropical America. They are, based on their agronomic performance (dry-matter production, leafiness, drought resistance, tolerance to insect pests and diseases, regrowth potential): *Flemingia macrophylla, Cratylia argentea* and the new *Calliandra* species for both the subhumid and humid zones; *Desmodium velutinum* and *Tadehagi triquetrum* for the subhumid tropics; and *Codariocalyx gyroides* for the humid tropics.

Based on their nutritive quality, however, not all of these species can be considered as promising fodder plants: the forage value of *Flemingia macrophylla, Calliandra* sp.n. and *Tadehagi triquetrum* is severely constrained by contents of condensed tannins that can be very high, leading to digestibilities as low as 20% (*F. macrophylla*) and by extremely low acceptability by livestock. In contrast, *C. argentea* and *D. velutinum* have no measurable tannin contents, and that of *C. gyroides* is low to intermediate (Lascano and Spain, 1992; Lascano *et al.*, 1995).

These promising species are briefly presented as follows:

Flemingia macrophylla (syn. *F. congesta*). Rather than a forage plant, due to its high tannin content this species is to be considered a multipurpose shrub with a potential to provide long-term effect mulch for soil improvement, weed control, moisture conservation and soil temperature reduction, based on the slow decomposition rate of the foliage (Budelman, 1991). Additional, important roles are erosion control in the form of contour hedges and the provision of shade in young coffee etc. plantations (Budelman and Siregar, 1992). Further research into the tannin issue, however, seems to be warranted in view of the remarkable agronomic characteristics of the species. Available germplasm is quite variable in many respects, e.g., leaf percentage (Figure 1), and should also be screened for lower tannin contents and higher digestibility. In this context, broadening the genetic base of presently available germplasm through further collection in the species' centre of diversity, tropical Asia, might be worth of consideration.

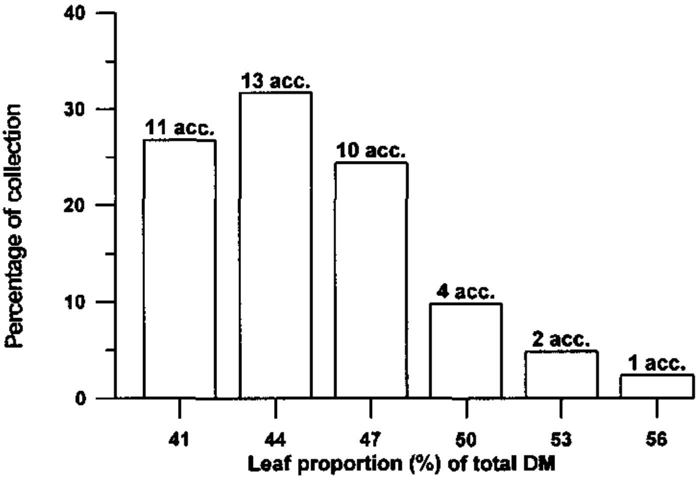

Figure 1. Variability in a germplasm collection: Frequency distribution of leaf percentage in a collection of 41 accessions of *Flemingia macrophylla* (R. Schultze-Kraft and G. Keller-Grein, unpubl.)

***Calliandra* sp.n.** This new, yet undescribed *Calliandra* is represented by only one germplasm accession, CIAT 20400, collected in a high-rainfall area in Tabasco, Mexico (Schultze-Kraft, 1991). Tannin contents are similar to those of *F. macrophylla* (Lascano and Spain, 1992) and the species should therefore probably be regarded in a similar manner. As it is closely related to hybridizing *C.*

calothyrsus (H.M. Hernández, pers. comm. 1990), it might be a useful gene donor to improve acid-soil adaptation of the latter.

Tadehagi triquetrum (syn. *Desmodium triquetrum)*. This subshrub is another species with high tannin contents (Lascano *et al.*, 1995), although in its centre of origin it has been found to be readily eaten by livestock grazing fallow vegetation. In none of the evaluations in tropical America it was very productive, but in subhumid savanna environments it shows a remarkable ability to persist and to spread through seeds. This might indicate the species' potential for fallow improvement.

Codariocalyx gyroides (syn. *Desmodium gyroides*). This rather well-known, leafy forage shrub of Southeast Asian origin has good adaptation to seasonally poorly drained soils. However, it is only a weak perennial, and its persistence is furthermore endangered because of susceptibility to root-knot nematodes (Soedomo, 1992). On the acid soils of the humid-tropical Caquetá region, Colombia, it is showing considerable promise in on-farm evaluations (J. Velásquez, pers. comm. 1996). Although the relatively small germplasm collection that is presently available (27 accessions) is quite variable in a number of agronomic characteristics, efforts to broaden the genetic base of *C. gyroides* by further germplasm collection in the species' centre of diversity seem to be justified.

Cratylia argentea (syn. *C. floribunda*). As early as in the 1940's, this South American species was identified as a particularly drought resistant, promising forage shrub legume in Brazil (de Otero, 1961), but it has only recently been rediscovered as a high-potential species for acid soils, mainly in subhumid savanna climates (e.g., Xavier *et al.*, 1995). Outstanding characteristics are leafiness, tolerance to drought and fire, absence of major biotic constraints, and an excellent regrowth potential after close cutting. Its forage value is very high in terms of crude protein content, but dry matter digestibility is intermediate to low. There are no detectable tannin contents but the acceptability of young, unwilted foliage by livestock is limited (Raaflaub and Lascano, 1995). The available germplasm collection is small but quite variable as some of the preliminary evaluation results suggest (Table 4). In the meantime, the genetic variability has increased considerably through plant exploration efforts in Brazil during 1994/95 (E.A. Pizarro, pers. comm. 1996). On-farm trials are now warranted to develop appropriate utilisation strategies and to assess the species' animal production potential.

Desmodium velutinum is a subshrub/shrub from tropical Asia and Africa which only occasionally has caught the attention of forage scientists (e.g., Asare *et al.*, 1984). In none of the evaluations on acid soils it was outstandingly productive. However, the finding that it is one of the very few, acid soil-adapted, shrubby legumes free of tannins, might foster new interest in the species. At CIAT there is a fairly comprehensive germplasm collection available – mainly of Southeast

Asian origin – which in several important characteristics such as crude protein content in leaves (Figure 2) shows a high degree of variability.

Table 4. Dry-matter (DM) yield and leaf percentage, contents of crude protein (CP), P and Ca, and *in vitro* dry-matter digestibility (IVDMD) of 3-month old regrowth of 11 *Cratylia argentea* accessions on an acid (pH 4.4), highly Al-saturated (89%) Ultisol in Colombia (R. Schultze-Kraft and G. Keller-Grein, unpubl.)

Accession no. (CIAT)	DM yield (g/plant)	Leaf %	CP (%)	P (%)	Ca (%)	IVDMD (%)
18668	332.1 a*	63	29.8	0.21	0.57	53.2
18671	217.8 ab	57	26.6	0.17	0.67	48.4
18676	200.0 ab	62	25.9	0.16	0.60	38.9
18675	183.5 ab	68	25.0	0.21	0.52	46.9
18672	181.6 ab	59	26.8	0.22	0.52	38.3
18674	163.8 ab	66	22.6	0.20	0.56	47.2
18957	155.2 ab	67	23.8	0.20	0.62	44.3
18673	153.3 ab	68	22.6	0.20	0.56	40.3
18666	152.3 ab	65	25.4	0.14	0.62	41.2
18667	121.6 b	66	24.1	0.16	0.57	41.2
18516	111.5 b	63	23.6	0.20	0.62	41.7

* a, b: significantly different at $P<0.05$

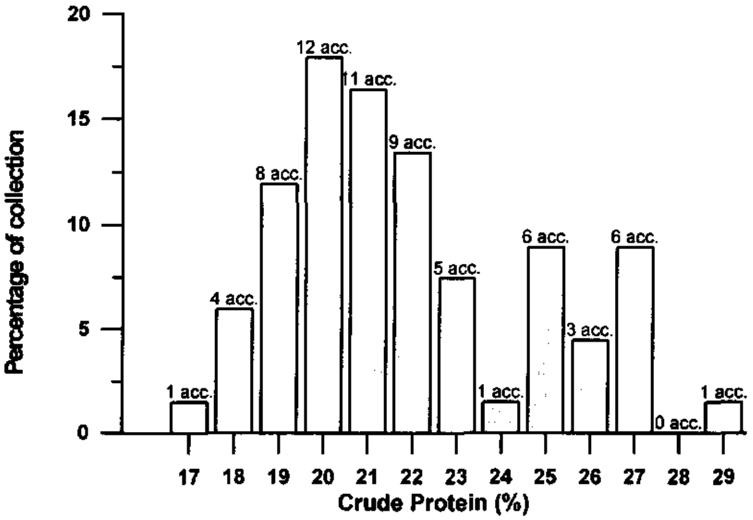

Figure 2. Variability in a germplasm collection: Frequency distribution of crude protein content (%) in a collection of 67 accessions of *Desmodium velutinum* (R. Schultze-Kraft and G. Keller-Grein, unpubl.).

Conclusions and outlook

In an attempt to draw summarizing conclusions from the work conducted so far on tropical legume shrubs for acid soils and to suggest future research, the following observations are offered:

- There are now several options available for new, promising legume shrubs for acid, low-fertility and highly Al-saturated soils in the tropics. To further explore their potential, research on agronomic management, mainly for cut-and-carry systems, and on animal production is needed.
- To increase the probability of adoption of a technology based on acid soil adapted shrubs – and learning a lesson from the acceptance difficulties of the alley-farming technology (Carter, 1996) – farmers should be as much involved in future research as possible. Such a participatory-research approach seems to be especially important in the area of the soil-improving effect of the legumes and other non-forage uses of the promising species.
- Data available to date suggest that the potential dry matter yields on such soils are substantially inferior to those known from species such as *Leucaena leucocephala* on non-acid soils. Therefore, as far as labour-intensive cut-and-carry systems are concerned – even at the subsistence-oriented production level – the economics of the use of the new species should be analysed. It is suggested that their potential might be highest under conditions where (a) the seasonally alleviation of feed constraints is a matter of livestock survival rather than "only" production, and/or (b) where there is a clear additional, multi-purpose related benefit for the farmer.
- Selected germplasm of the promising species should be tested in a correspondingly wide range of environments in order to explore the limits of edaphic and climatic adaptation, and to identify possible biotic constraints. For this, a network approach with a common evaluation methodology is suggested, and the species should be compared with material released from breeding programmes such as that of *L. leucocephala* (Hutton and Chen, 1993).
- Research on the mechanisms of adaptation to acid soils is also indicated, particularly with regard to the effects of the individual components of the "acid, infertile" soil complex.
- For all species, broadening the genetic diversity available for research through further germplasm collection in the species' centres of diversity, mainly Southeast Asia, is suggested.
- Regarding the high tannin contents of some of the species, suggested research topics at a level other than rumen physiology are the use of legume mixtures (Fässler and Lascano, 1995), post-harvest treatments, exploration of the intraspecific diversity, and the relevance of genotype x environment interactions.

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The wealth of forage plant species

L.J.G. van der Maesen

Department of Plant Taxonomy, Wageningen Agricultural University,
P.O. Box 8010, 6700 ED Wageningen, The Netherlands

Abstract

Plant species that serve as forage and fodder form part of widely different plant families, and usually serve other purposes as well. Many forages have an auxiliary role in agriculture and forestry, and vice versa. *Gramineae* and *Leguminosae* are by far the most important taxa harbouring forage species, but whereas within *Gramineae* no particular group is more important in this respect, in *Leguminosae* the tribes *Phaseoleae*, *Aeschynomenae* and *Desmodieae* contribute more forages in the tropics than any other tribe, while in temperate zones the *Vicieae* and *Trifolieae* play this role. Some inventories illustrate the distribution of species over families and tribes.

Selection of genotypes adapted to local conditions and the testing of species that so far received little research attention, hold promise for the improvement of grass- and rangelands particularly in the tropics. The availability of genetic resources is still very unevenly divided over the taxonomic groups. Nature still has a wealth of forage species of benefit to man's animals.

Introduction

Species belonging to many plant families serve as forage and fodder for animals, and are as such indispensible in the food chain. The grass family (*Gramineae* or *Poaceae*) and the legumes (*Leguminosae* or *Fabaceae* s.l.) play a predominant role in both natural and improved pastures. Which species are most important? In this commodity group quantitative data are difficult to generalize, but a few handbooks give some leads by their mere inclusion in these books. Without even trying to be exhaustive, this paper gives some indications which species are important, and establishes their taxonomic position in the plant kingdom.

As far as statistics go, the number of cattle and acreage of pastures is obtainable in the temperate zones. In the tropics the number of cattle or wildlife is statistically also more manageable than forage production, in temperate zones semi-monoculture pastures are well-known productionwise. For example, the perennial ryegrass *Lolium perenne* L. covers 1.1 million ha in the Netherlands alone ('t Mannetje, 1994), either in mixtures with other grasses and/or clovers, or as monocrop, making it the largest crop area-wise in the country (Loos, 1994). Sport fields (20,000 ha), lawns (30,000 ha) and roadsides (50,000 ha) contain considerable proportions of *L. perenne* also, up to 75%, 60% and 20% respectively (Ebskamp *et al.*, 1995). Quite a few cultivars have been selected for specific purposes. In 5% of the sowing seed mixtures sold *Trifolium repens* L. is added.

Forage species

Species important as forage

Before we address the question which species are important or promising, a few general remarks. Many species are well-known for forage and pastures, but scientific attention is spread very unevenly because of the large number of used and potential species. Both domestic animals as well as game and other wildlife share the resources of such a rich and varied genetic diversity. Here, as always, taxonomy is the basic tool to communicate, and perhaps even more important than with most of the food crops. For food crops the common name is usually well-known, whereas with forage plants a vernacular generic name does not suffice to identify the species.

Grasses as forage

Why are (mainly perennial) grasses so successful as forage and fodder? Their ability to withstand grazing, by producing new shoots and tillers almost *ad libitum* from the meristematic region at the base of the internodes, by regrowth after a dry or cold season or the passage of fire, by the ability to be processed into hay or silage, promoting seasonal availability, these aspects are just a few characteristics that most grasses have in common. Their carbohydrate and fibre contents are high, proteins are lower than in e.g. legumes, but reasonable in the seeds. Importantly, the seeds are of "orthodox" constitution and can be stored easily after proper drying. However, the nutritive quality of most tropical grasses is relatively poor, reducing the carrying capacity per unit area. As C_4 grasses they have a more robust anatomy with less mesophyll, more sclereid fibres and vascular bundles, and thicker cell walls than C_3 grasses from the temperate zones, and are therefore less digestible.

Legumes as forage

Why are legumes so successful as forage and fodder? In combination with grasses, either mixed in the sward or as separate shrubs and trees in savanna and forest, they often provide palatability and always protein, and so increase the quality of the diet. High in nitrogen content, most species are generally low in toxic matter. Many genera play a useful role as forage either as primary or auxiliary purpose. The role in improving soils by nitrogen symbiosis in mixtures or as sole green manure or cover crop is well-known.

In tropical rain forests up to 30% of the biomass may be contributed by leguminous trees, often of the subfamily *Caesalpinioideae*. As food for wildlife and lower animals these are certainly important.

Even more than grasses, legumes are multi-purpose species. While preparing PROSEA Handbook Vol. 11 on auxiliary plants, much attention was given to defining the role of primary and secondary functions of the species to be included. These roles also depend on the production system in which the plants are used. The groups of auxiliary plants which we distinguish are: shade and nurse trees, cover crops, green manure, mulch, fallow crops, live fences, windbreaks and shelterbelts, erosion-controlling plants, live support and stakes, and fuelwood. In the category water-clearing agents no legumes play a role, but reeds (*Phragmites australis* (Cav.) Steudel) and bulrushes (*Scirpus* spp.) are important here, and even these have forage value. With the exception of fuelwood, auxiliary plants do not deliver primary products (van der Maesen *et al.*, in press), but quite a few of them are valuable for forage.

Other families providing forage

A large array of other families provide food or fodder plants, but in quantity these most likely lag behind grasses and legumes. An exception may be the tropical rain forest, where wildlife consumes an extremely diverse array of leaves, fruits and even bark and branches. In Australia, *Eucalyptus* is the sole food of the Koala bear, its aromatic oils prohibiting most other animals and insects from using these species as food. Co-evolution made some species of animal into specialists, other ingest food from many plant groups. These are obviously not treated as forage in the sense of commodity group (e.g. 't Mannetje and Jones, 1992), where virtually all non-poisonous plants can be considered forage. In their PROSEA volume on forages, only four species from other families are tabulated as forage for Southeast Asia, against 29 native grasses, 36 selected (improved or/and introduced) grasses, 8 shrub legume species, and 44 herbaceous legumes (Table 1). The list of minor forages presents mainly grasses, a few legumes, and 43 species belonging to other families. In the list of forages with another primary use, 178 species from other families are included, mainly of higher plants.

In East Africa, the role of legume species in grassland is sometimes estimated to be relatively unimportant compared with the grasses (Boonman, 1993), but this opinion does not find wide acceptance. Legume persistence leaves to be desired in this area, and palatability of legumes is considered less favourable than in general. As a result 48 native or naturalized grass species are treated, and 8 introduced grasses, against

Table 1. Taxonomic distribution of forages as treated in Prosea volumes 4 and 11.

Family	Source	Prosea Forages Number of species	Prosea Auxiliary Plants Number of species *)
Major forages			Major auxiliary plants
Grasses: *Gramineae*		65	6
Legumes: *Leguminosae*		52	55
Other families		4	51
Minor forages			Minor auxiliary plants
Grasses: *Gramineae*		193	51
Legumes: *Leguminosae*		10	6
Other families		43	51
Forages with other primary uses			Auxiliary plants with other primary uses
Grasses: *Gramineae*		23	25
Legumes: *Leguminosae*		54	69
Other families		178	200

*) Many auxiliary plants, but not all, are edible as forage. Figures semi-final.

16 legume species, all herbaceous plants except *Leucaena leucocephala* (Lamk) de Wit.

Native or introduced species?

Imported species are often more aggressive outside their native habitat, a characteristic wanted for improvement of pastures where e.g. native legumes have less competitive ability than the prevalent grasses. The incidence of diseases and pests is often lower with introduced species. When native species are preferred for reasons of avoiding the importation and spread of invasive species, one usually has to reckon with lower yields.

Quality of dairy products

An interesting question is the role various plants have in determining the final quality of the meat and dairy products. It is generally known, that a varied diet and the presence of herbs produce better flavour in the end products, such as the difference of cheeses produced from hay- versus pasture-fed cows, or the taste of wild versus farm-bred pork. There is little scientific research, if any, to substantiate this (S. Tamminga, pers. comm.), and since so little is known about the very substances involved, it is a complicated question to tackle. However, in a generalized sense a varied forage diet is as beneficial to animals as a varied and balanced diet is to humans. Animals have a strategy to survive, and select their forage as far as possible. The liberty to move around, and being able to select certain plants, certainly adds to the general constitution of animals. It is strategic to use the diversity within and between species as much as possible to reduce the risk of reliance on a narrow diversity and to increase the quality of life of the animals and their products. The special cheese ("May or grass cheese") produced from the milk in spring, when cows are pasture-fed after a winter of silage, hay and other dry fodders, is appreciated for its taste and sold separately. Emmenthal cheese in Switzerland is even produced with milk from cows fed with hay or fresh forage only, as silage may contribute butyric acid spores, which spoil the cheese.

Thereagainst it is common to mix milk products, to obtain an industrially homogeneous end-product over time. In ruminants there is less effect of forage quality or the presence of herbs on the quality of milk or meat than in mono-gastrics.

Taxonomy

What is the taxonomic position of grass and legume species?
In *Gramineae* species of the *Bambuseae* tribe are the specialty food for the Panda bear (although not exclusively so), and few other animals can digest their stems and leaves. Otherwise, no grass tribe includes species of particular palatibility.
In *Leguminosae* the species of the subfamily *Papilionoideae* are usually the most useful ones for forage, as 97% of the examined species have symbiotic properties, against 90% in the *Mimosoideae* and 23% in the *Caesalpinioideae* (Faria *et al.*, 1994; Allen and Allen, 1976 calculated 98, 90 and 30 % respectively). Sofar, only 20% of the legume species have been investigated for *Rhizobium*, *Bradyrhizobium* and/or myccorhiza symbiosis. The mimosoid and caesalpinioid subfamilies harbour more woody species, and do not have a large primary role as forage, but provide timber, hedges and fences, fuelwood etc. In non-nodulating *Caesalpinioideae* mycorrhizas appear to be important and economical in rain forest as well as in dry areas (Sprent, 1994), and are suspected to play a role in the often gregarious occurrence of a number of species.

Of the genera that are important as forage or browse several contain many species: *Tephrosia* (400 spp.), *Desmodium* (300 spp.), *Indigofera* (700 spp.); *Aeschynomene, Vicia, Trifolium* have between 150 and 300 species, *Crotalaria* has more than 600 species, and *Acacia* s.l. counts over 1200 species.

In contrast to the palatable species, some very inedible legume species also exist in the same genera that provide edible ones, and some are even poisonous. Unpalatable species are useful as cover crop to protect erosion-prone areas. A conspicuous example is *Cadia purpurea* (Picc.) Ait. from Ethiopia and Yemen, that is not even touched by goats. It is not known, whether other genera in the Cadia-group of the *Sophoreae* tribe (*Papilionoideae*) harbour edible species.

Taxonomic research and revisions

What systematic problems remain in forage species? In the legumes an obvious example is *Stylosanthes*, a genus important for forage plants, having been studied by 't Mannetje since long (1967, 1969, 1977, 1984). General species relationships and the circumscription of some taxa leaves to be desired (such as the different cytotypes in *S. hamata* (L.) Taub. and the relationship between *S. fruticosa* (Retz) Alston from Africa and *S. scabra* Vog. from South America). Phylogenetic research using chloroplast DNA variation is in progress to elucidate the taxonomic status of these and other species or varieties within *Stylosanthes* (Gillies and Abbott, 1996).

Table 2. Taxonomic distribution of forage legume species.

	Source	PROSEA Forages		PROSEA Aux.		E.Afr.	Trop. Legumes		Fl. Ned.
Tribe	Major	Minor	Second	Major	Minor		Pasture	Browse	
<u>*Caesalpinioideae*</u>									
Caesalpinieae	-	-	4	1	1	-	-	-	-
Cassieae	1	1	2	7	3	-	-	2	-
Cercidae	-	1	-	-	-	-	-	6	-
Detarieae	-	1	1	-	-	-	-	1	-
Macrolobieae	-	-	-	-	-	-	-	1	-
<u>*Mimosoideae*</u>									
Parkieae	-	-	-	-	-	-	-	-	-
Mimoseae	3	-	3	1	4	1	1	7	-
Acacieae	-	-	4	7	5	-	-	46	-
Ingeae		2	-	3	1	5	-	-	5
	-								
<u>*Papilionoideae*</u>									
Sophoreae	-	-	1	-	-	-	-	1	-
Dalbergieae	-	-	1	-	2	-	-	-	-
Tephrosieae	-	-	3	4	4	-	-	2	-
Robinieae	3	-	2	-	-	-	-	4	1
Indigofereae	-	2	1	3	2	-	1	-	-
Desmodieae	9	2	2	2	6	2	13	6	-
Phaseoleae	16	1	17	8	17	5	29	3	3
Aeschynomeneae	10	-	2	1	2	3	11	1	-
Vicieae	-	-	-	-	-	-	-	-	24
Cicereae	-	-	1	-	-	-	-	-	1
Trifolieae	3	-	1	-	1	-	-	-	29
Crotalarieae	2	-	4	11	4	1	1	-	-
Genisteae		1			1				10
Others							1		9

Sources: Prosea Vol. 4: Forages: 't Mannetje and Jones, 1992; Prosea Vol. 11: Auxiliary Crops: van der Maesen and Hanum-Ibrahim, in press (semi-final figures); Boonman, 1993; Skerman 1977; van der Meijden, 1996.
The tribes are in systematic order, to display relationships (Polhill and Raven, 1981; Breteler, 1995).

Table 3. The state of the world's forage genetic resources.

Grasses		
Andropogon	1,500	
Bromus	4,500	
Cenchrus	2,000	(52% wild species)
Dactylis	27,000	(41% landraces)
Elymus	2,500	
Festuca, fescue	24,000	(18% landraces)
Lolium, ryegrasses	24,000	(11% landraces)
Panicum	21,000	(3% landraces)
Phleum, Timothy grass	9,000	(53% landraces)
Poa	8,000	(28% landraces)
Other grasses	18,000	(63% wild species)
Legumes		
Lathyrus sativus, grass pea	13,000	(62% wild species/accessions)
Lotus corniculatus, trefoil	3,500	(unknown)
Medicago, medics	33,000	(31% wild species)
Trifolium, clovers	64,000	(14% wild species)
Vicia, vetches	26,500	(27% wild species)
Other legumes	31,000	(92% wild species)

Source: WIEWS Database, FAO, 1996.

Modern taxonomic treatments may have upset traditional usage of species names: *Cassia* s.l. is now subdivided into the former subgenera *Cassia* s.s., *Chamaechrista* and *Senna*. *Chamaecrista rotundifolia* (Persoon) Greene is a very useful herbaceous legume and *Chamaechrista mimosoides* (L.) Greene is palatable as forage shrub. *Cassia siamea* Lamk, apart from being a beautiful ornamental, is a useful browse, just as so many other leguminous trees. The subdivision is supported by molecular and nitrogen-fixation data. *Leucaena leucocephala* (Lamk) de Wit, as the correct name for the shrub or tree long known as *Leucaena glauca* (Willd.) Benth., is now well established, but it took time to filter through to general users. In time, new treatments get accepted also by non-taxonomists.

The tribes that harbour forage legumes are not spread evenly throughout the family. Tables 2 and 3 present some information, it is clear that most herbaceous forage legumes belong to the tribe *Phaseoleae*. The framework of tribes is not expected to undergo major further changes in the near future, but adjustments are certainly possible (e.g. Breteler, 1992; Crisp and Doyle, 1992).

Genetic resources

With the urge to improve pasture vegetations the Australians (CSIRO) have played a prominent role, thereby also introducing odd simplifications of the scientific name as common name: Scrobic (*Paspalum scrobiculatum* L.), Hetero (*Desmodium heterophyllum* (Willd.) DC), Stylo (*Stylosanthes guyanensis* (Aubl.) Sw.), Centro (*Centrosema pubescens* Benth.).

With cattle and sheep ranching as a major agricultural activity, the pasture improvement programmes in Australia are unparalleled, focusing on both introduced and native species. Annually some 500 000 ha are sown to legume-based improved pastures in northern Australia, whilst annual seed production amounts to a potential area of some 1.5 million ha (Smith, 1996). The Australian germplasm collection activities spread out to all continents, just as is also the policy of the Centro Internacional de Agricultura Tropical (CIAT) in Colombia, which has the largest seed collections of tropical legumes among the international agricultural research centres. However, because of the wealth of species, many species have little or no representation in genetic resource collections. Specific diversity is largest in the gene bank at Wakehurst, belonging to the Royal Botanic Garden at Kew in England, but here just a few representatives per species are kept.
The whereabouts of genetic resources of many auxiliary plants can be found in the Forages volume of the IBPGR (now IPGRI) Directories of germplasm collections (Bettencourt *et al.*, 1992) including most relevant legume species, many browse plants also including legumes and forage grasses. Country-wise the various institutions are listed, showing the wealth of diversity available particularly in Colombia, the United Kingdom and Australia. Usually more than 82% of the samples are freely available. Roughly 34% of the samples is duplicated in other collections for safety reasons.

Conclusions

In the tropics the *Phaseoleae, Aeschynomenae* and *Desmodieae* contribute more species as forage than any other tribe. In the temperate zones the *Vicieae* and *Trifolieae* are important.

It can be stated once again that legumes and grasses provide mutual benefit in systems to provide forage, and sustainable pasture systems. With the attempts to reduce the supply of industrial nitrogen fertilizers to protect soil water from pollution in temperate zones, the role of legumes may assume more importance. The use of legumes in mixed pasture leads to the reduction of fertilizer inputs, hence transportation and fossil fuels. On the other hand the mineralization of organic matter originating from *Rhizobium* root nodules and clover stolons in autumn may also lead to leaching of nitrate substances, as is the case with inorganic nitrogen from industrial fertilizers. As such pasture with clovers are not more environment-friendly, and biologically fixed nitrogen cannot be rationed in amount and time, as fertilizers.

In tropical zones, where legumes have made intensification of agriculture possible before the fertilizer era, and often still maintain soil fertility at some acceptable level for subsistence farming, the sheer number of possible combinations of grass and legume species indicate that not all of these can possibly have been tested everywhere. To conclude that the "wonder legume" is not likely to be found, after a century of forage research, is premature. New pasture legumes are continuously being developed such as *Arachis pintoi* Krap. & Greg. (Kerridge and Hardy, 1994) and new suggestions for use as forage or green manure are being made, such as species of the genera *Codariocalyx, Cratylia*, and *Tadehagi* (Schultze-Kraft, this volume). Further, it hardly seems a coincidence, that many forage legumes are related to the bean tribe, the *Phaseoleae*, that harbours quite a few tasty vegetables.

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Grassland science, does it exist ...?

L. 't Mannetje

Department of Agronomy, Wageningen Agricultural University,
Wageningen, The Netherlands

Abstract

Gramineae are important sources of human and animal food and grassland-based animal production is the most important form of livelihood for people in cold and dry climates. Integration of crop and forage-based animal production lead to more sustainable agriculture than either of them separately. Permanent grassland is an important sink for carbon.

Grassland science links plant and animal production, serves nature conservation and the management of amenity grasslands. Grassland science is practiced at scales ranging from the cell wall to world regions. Physiology of grassland plants deserves special attention because the *Gramineae* contain both C_3 and C_4 plants, which has important implications for grass production and nutritive value. Morphological and physiological grassland plant development have a strong influence on production, sward quality and digestibility of forage. In intensive grassland farming with high levels of nitrogen fertilizer, forage digestibility is high, but the protein:energy ratio is too large, causing inefficient nitrogen use and emission of ammonia to the environment.

Legumes are important for grassland production, particularly in tropical climates. Legumes fix nitrogen and have a high nutritive value. For tropical climates there are legume cultivars with better grazing tolerance than in the past. *Arachis pintoi* is a recently developed, tropical pasture legume for humid and subhumid climates with high productivity, nutritive value and grazing tolerance. Also for western European conditions new cultivars of *Trifolium repens* are available with better persistence. The main shortcoming of legumes for intensive grassland production is the inability to regulate the amount and timing of nitrogen availability from a point of view of production as well as emissions to the environment.

Grassland soils release nitrous oxide and forage fed ruminants produce methane, which contribute to an increasing greenhouse effect. However, grassland soils store large quantities of carbon, which counter these negative effects. In tropical regions,

legume-based grassland improvement considerably increase this carbon storage capacity.

Grassland production in The Netherlands faces increased costs due to stringent environmental protection measures. The nitrogen surplus on dairy farms can be reduced by reducing stocking rate. However, this requires more land per farm in order to meet economic sustainability. Mixed farms are in a better position to meet these restrictions. Because the nitrogen supply needs to be exactly managed in terms of quantities and timing, there is no place for pasture legumes, except on "organic" farms.

Forage-based animal production in the tropics lags behind temperate regions due to poor nutrition and inadequate management. There is a need for better forage production to meet population growth and increased purchasing power in many developing countries. In order to halt the destruction of forests and rangelands for increased food production, both crop and grassland production need to be intensified. Unfortunately, socio-economic constraints in developing countries hinder the adoption of sustainable grassland improvement.

The merger of the chairs of Field Crop Science and Grassland Science at the Wageningen Agricultural University is not logical because of differences between the areas of concern. It would have been better to maintain one chair for each of Crop Science, Plant Breeding and Grassland Science, which would also have led to the saving of an extra chair.

Introduction

Gramineae are the sources of most human and animal food: the cereals, most of the sugar and the forage for domestic and wild herbivores. Animal production from grasslands is important for the livelihood of people in dry and cold climates, where crop production is not possible. Crop and animal production can be integrated to more sustainable agriculture than either of them separately. Crop production benefits from animal production in the form of draft power, manure and the possibility to apply crop rotation with grassland soils of high organic matter content, with better water and nutrient holding capacities and nitrogen becoming available from mineralisation. Animal production benefits from crop production by supplying crop residues and forage crops. In tropical regions with intensive field and plantation crop agriculture, animal production is an important way for small farmers to increase their income and relieve their poverty, because animals can utilize forage produced on wasteland and crop residues. Baars (1996), referring to rangelands and animal production in Zambia stated: "Milk and meat are important food items, oxen the only form of draft power, manure the only source of nutrients and fuel, and the sale of animals the only source of cash". Permanent grassland and forests are the most important terrestrial stores of carbon. The destruction of one hectare of grassland has comparable consequences for the greenhouse effect as that of one hectare of forest. Permanent grasslands offers the best protection against erosion. Some attention for grassland is clearly warranted.

Grassland science

The basic sciences for grassland science are plant physiology and ecology. Grassland science is production oriented to animal nutrition, husbandry and production. Grassland science links plant and animal production, with the grazing animal as the interface. Grassland science is also concerned with nature conservation: the ecology and management of grass vegetations on farms with a dual purpose of production and nature conservation.

An important area of concern for grassland science is recreation: lawns, playing fields and other amenity grasslands (Minderhoud *et al.*, 1989). The significance of grasslands has been given world wide publicity during the recent European Soccer Championships tournement in England. Of the 8 soccer fields used for this tournement 6 were sown with special cultivars bred by a Dutch company. Playing fields which are so intensively played upon need to be able to recover quickly. This means that the grass species and cultivars must have a rapid regrowth and be able to withstand heavy treading and frequent short cutting.

Defoliation in the form of grazing and cutting influences vegetation composition and dry matter yield, by varying its intensity and frequency. For production pastures the objective is to achieve a high yielding, homogeneous mixture of a small number of grasses and legumes. For nature conservation a multi-species composition of grasses and dicotyledons is generally the aim, which can be more easily achieved at low nutrient input levels, resulting in low dry matter yields (Bakker, 1994).

Grassland science operates at different scales:

Scale	**Objective**
Cell wall	Digestibility
Leaf and stem	Development, anatomy, digestibility
Tiller	Leaf development, tillering, digestibility, sward density
Field	Botanical composition, yield
Farm	Grazing/cutting regimes
Region	Carrying capacity

Grassland science, like other agronomic sciences, integrates other sciences and focuses on dry matter production and quality, on botanical composition and density of the sward, and on management of grassland vegetations. Grassland science can be divided into: physiology, ecology, production, quality, conservation and utilisation of forage.

Grassland physiology

There are some aspects of plant physiology in relation to grasses, which deserve special attention and which have great influence on the production and quality of forage. These concern photosynthesis and plant development. Most angiosperms possess the C_3 pathway of photosynthesis, but the family of *Gramineae* contains both species with the C_3 and C_4 pathway (Whiteman, 1980).

C_4 grasses (in comparison with C_3 grasses):

* grow mainly in tropical climates;
* require higher temperatures for growth and are therefore less digestible;
* have a more efficient water use;
* produce more dry matter per unit of time and area;
* have a greater nitrogen efficiency and as a result a lower crude protein concentration;
* have lower carbohydrate reserves;
* have thicker cell walls, less mesophyll, more sclerenchyma and more bundle sheaths and as a result a lower digestibility.

The C_4 characteristics concerning growth, production, water and nitrogen efficiency are favourable, but the lower carbohydrates and protein concentrations and lower digestibility are clearly unfavourable for the nutritive value of C_4 forages. The relatively low soluble carbohydrate content also means that it is more difficult to ensile tropical grasses (Catchpoole and Henzell, 1971). As a consequence of the relatively low digestibility and the low crude protein concentration of tropical grasses, it is very important for animal production that tropical grasslands contain legumes, or that the animals have access to protein banks: monocultures of legumes (usually shrubs). Legumes and the tropics will be discussed below.

Development of the grass plant

Plant development is one of the factors determining dry matter yield, sward quality and digestibility of forage. Since the different plant organs differ in digestibility, and ageing of these organs reduces digestibility, the morphological development of the plant is very important for the quality of forage.

Most C_3 grasses show stem elongation only when they are about to flower. Perennial ryegrass, the grass species with the highest nutritive value, exhibits stem elongation only after vernalisation, and at a critical daylength inducing inflorescence formation. As a consequence, stems are present only during a short time in spring and early summer. Since stems are lower in digestibility than leaves, perennial ryegrass has a high digestibility during the whole growing season in western Europe. Furthermore, the lack of stem elongation means that the growing points are close to ground level and thus protected against loss due to grazing and cutting.

In contrast to C_3 grasses, most C_4 grasses, growing in the tropics, are very stemmy, because stem elongation takes place irrespective of flowering. As a result, these species have a lower stem:leaf ratio, which also contributes to a lower nutritive value of tropical grasses (Dirven, 1977).

Tillering or tiller density of C_4 grasses are much less than of C_3 grasses, which also causes lower sward density. Tillering is important for soil cover and dry matter yield. Tillering results in the addition of more new phytomeres (plant parts with stems, roots, leaves and inflorescenses) per unit area. Since a tiller can only have a limited number of leaves, there is a rapid replacement of the leaf canopy. The art of grassland management for animal production is to harvest as many leaves as possible by grazing or cutting before they senesce. Tiller density is a function of the formation and death of tillers, which in turn depends on leaf formation. Tiller formation occurs by the development of buds in the axils of leaves. A measure of tillering is "site filling", the willingness of axillary buds to develop. Site filling is affected by light interception and nitrogen, therefore by management (Neuteboom and Lantinga, 1989).

Another aspect of plant development is the ability of many grasses to spread vegetatively through stolons and rhizomes. These are important characteristics determining ground cover. The resulting dense sward prevents the invasion by other species, i.e. fewer weeds, but also causes greater difficulty to introduce legumes.

The production and quality of forage

A paddock of grassland forage in western European intensive agriculture can be regarded as a crop, whose dry matter yield depends on temperature, light interception, soil moisture, soil fertility and harvest frequency and intensity. However, it is different from a field crop, more comparable to a tea plantation, because grassland is a (semi)permanent vegetation, whose assimilation apparatus, the leaves, are also the harvestable product. Most field crops are sown annually, fertilized, weeded and protected against pests and diseases. After weeks or months the product, usually the fruit or underground organ, is harvested and the field becomes vacant again. Grassland sward management consists mainly of fertilisation and sometimes topping.

Weed control is usually only practiced with newly established swards, except in the wet tropics. When the sward contains too many undesirable species, it is usually newly planted after chemical or mechanical killing of the existing sward.

Grassland fertilisation is important because of its large effects on dry matter yield and nutritive value, which is strongly dependent on the age of the forage, and on the emission of nutrients. Fertilisation must be based on a compromise between yield and quality on the one hand and limited emissions to the environment on the other ('t Mannetje and Jarvis, 1990).

Modem, technologically based dairy farming with optimal fertilisation and management, produces forage of high digestibility. However, this product contains too much protein for the amount of available energy in the rumen. The rumen microbes are not able to convert all the nitrogen into microbial protein. As a result, a relatively large amount of nitrogen leaves the rumen as ammonia and is excreted as urea in the urine, which is largely responsible for the ammonia emission to the environment. Solutions to this problem are complex. Supplementation with energy-rich feedstuffs, e.g. maize, pulp and fodder beets, reduces the problem, but does not solve it entirely. At the moment research is in progress to increase the nitrogen efficiency of perennial ryegrass in order to achieve a smaller protein:energy ratio. This is also possible by reducing the nitrogen concentration in the forage, a.o. by reducing the level of fertilisation. However, there is the danger that the growth rate of the grass will be reduced, leading to older forage at the time of grazing or cutting. This will reduce the protein:energy ratio, but the question is whether this would not also reduce animal intake.

Grassland management has a big effect on the efficiency of nutrient utilisation and thus on the emission of nutrients to the environment. The main management options are: 1) the amount, the kind, the timing and method of application of fertilizer and especially manure and 2) the harvesting regime of grazing and cutting. Research into and application of measures to reduce environmental impact are more advanced in The Netherlands than in most other European countries, but there is also a greater need for it.

Legumes in grassland

Legumes belonging to the subfamilies *Papilionoideae* and *Mimosoideae* play an important role in grassland production. They fix atmospheric nitrogen in symbiosis with *(Brady)rhizobium* bacteria, have a high protein concentration, maintain their digestibility longer than grasses and enrich the soil with nitrogen ('t Mannetje *et al.*, 1980).

Nitrogen fixation by bacteria and photosynthesis are two processes, without which there would not be any life on earth. Thanks to nitrogen fixation the legumes are independent of soil nitrogen for their growth and persistence. Selected species and cultivars fix more nitrogen than is needed for their own growth and they build up soil nitrogen levels as a result. Grasses growing in association with legumes benefit from enhanced soil nitrogen after mineralisation of organic matter. This is particularly important for tropical grasslands in regions where nitrogen fertilizer is not profitable. Legumes have a high nutritive value because of their high protein concentration, which in many cases is less degradable in the rumen, and because of their C_3 type leaf anatomy. Animals consuming legumes have a greater potential for the uptake of less digestible feeds, such as crop residues and older grass. Intake of selected legumes by animals is also higher than that of tropical grasses, because the packing density in the rumen is higher. Furthermore, the digestibility of legumes declines more slowly with age than that of grasses (Minson, 1985).

There are many advantages in the use of legumes in grasslands. Since the 1960s research institutions in Australia and South America have successfully developed legume cultivars for (sub)tropical grasslands for all but the driest climates from wild species, often unknown to agriculture and sometimes unknown to science ('t Mannetje, 1984; 't Mannetje and Jones, 1992). The first generation of cultivars of tropical legumes was often not tolerant to heavy grazing and subject to pests and diseases. However, modern cultivars of several species have a high grazing tolerance and are resistant to pests and diseases (Cameron *et al.*, 1989; Gramshaw *et al.*, 1989; Tarawali, 1994; Jones and Bunch, 1995).

Also for western European grasslands there are now better cultivars of white clover than some 20 years ago. The Welsh Plant Breeding Station has collected new genetic material from which it has bred new cultivars which are more persistent than old ones (Rhodes *et al.*, 1989; Evans *et al.*, 1990; Frame, 1993). White clover in permanent grassland in The Netherlands over the last 8 years has persisted better than in the past, including the survival after severe winters (Elgersma and Schlepers, 1997).

The paper by Schulze-Kraft in this volume has paid adequate attention to legumes, so that I will not expand on them any further. However, I would like to eliminate a misunderstanding. The eminent C.T. de Wit once stated that there would not be a future for tropical pasture legumes, because being C_3 plants they would not be able to compete with C_4 grasses. There are indeed very aggressive tropical grasses, such as those belonging to the genus *Brachiaria*, which are difficult to combine with legumes. However, he overlooked the fact that legumes have a big advantage over grasses in being able to fix their own nitrogen. At any rate, there are now legume cultivars of several species, e.g. *Arachis pintoi*, which grow very well with aggressive grasses and are also tolerant to heavy grazing (Cameron *et al.*, 1989; 't Mannetje and Jones, 1992).

However, there are also negative aspects of the use of legumes. The main shortcoming is that it is not possible to regulate the amount of nitrogen in the system, because this is dependent on the growth and the proportion of the legume in the sward. These vary with the seasons and between years. Grassland management for the maintenance of a desired balance between grasses and legumes is very difficult compared with the management of fertilized grassland. Another disadvantage is that permanent grass-legume mixtures with a good proportion of legumes will cause serious soil acidification. This happened in southern Australia with subterranean clover (*T. subterraneum)*. After decades, the pH of the soil was too low for the survival of *Rhizobium* (Haynes, 1983; Hochman and Helyar, 1989). Fertilizer nitrogen, on the other hand, can be applied in optimal amounts and at the times required for forage production and to minimize emissions to the environment; in The Netherlands, nitrogen fertilizer is applied as a mixed fertilizer containing calcium, so that soil acidification does not occur.

The main advantage of biologically fixed nitrogen is the saving on energy for the manufacturing, transport and application of fertilizer.

Grassland production and the greenhouse effect

Grassland production influences the greenhouse effect because of: 1) the emission of N_2O during nitrification and denitrification; 2) a net emission of CH_4 by ruminants and from soils with high organic matter contents and a high water table; 3) the storage of carbon.

1) The emission of N_2O is related to the amount of nitrogen in the system. The ratio N_2:N_2O in denitrification is determined by the conditions for denitrification. As these become less favourable for denitrification, the proportion of N_2O increases. So, when denitrification decreases, e.g. as a result of low temperatures, higher oxygen pressures or low pH, there will be relatively more emission of N_2O than N_2.

2) CH_4 is emitted in anaerobic fermentation of carbohydrate compounds, therefore, by the digestion of feed in rumens, but also from irrigated rice production and from swamps and rubbish tips. In relation to grasslands, there are two interesting points. Firstly, the amount of CH_4 which is formed depends on the digestibility of the feed (Leng, 1993). Highly digestible grass and concentrates, as used in The Netherlands, produce less CH_4 (Goossensen and Meeuwissen, 1990) than poorly digestible grass such as occurs in unimproved grasslands and with crop residues in the tropics.

Therefore, it is not only important to improve grasslands in the tropics for higher food production, but as a side effect there will be less CH_4 emitted per kg of feed intake. The second point is interesting in relation to vague plans in The Netherlands to increase the soil water tables in peat grassland regions for nature development purposes. These regions will then have much higher CH_4 emissions (Van den Pol-van Dasselaar and Oenema, 1996). Good for nature, but bad for the greenhouse effect. There are more such examples of conflicting interests between deserving objectives.

3) Grassland soils store large quantities of organic matter and therefore carbon. The amount of carbon stored under a hectare of grassland in The Netherlands is comparable with that under a hectare of forest. Taking into account standing timber, forest is somewhat higher in total carbon stored (Goudriaan, 1990; Wolf and Janssen, 1991; Minami *et al.*, 1993). It has been measured in tropical grasslands that the addition of legumes to grasslands will strongly increase carbon storage. My former PhD student Muhammad Ibrahim (1994) has shown in Costa Rica that the soil under one hectare of *Brachiaria brizantha* with *Arachis pintoi* contains as much carbon as one hectare of rain forest in that region. Fisher *et al.* (1994) reported large amounts of C storage under a *Stylosanthes capitata* pasture in Colombia.

The future of grassland production in The Netherlands

The area of grasslands in The Netherlands is about 1 million ha, on which about 40 000 farmers produce milk and other animal products such as meat and skins. Milk production is limited by the EU milk quotum and farm income is under pressure from the high costs of labour and measures to curb emission of nutrients. Experts are of the opinion that the number of farmers will be reduced to half, with farms of at least 100 cows on at least 50 ha, producing 1 million kg milk per farm per year. The cost price of milk will also have to come down in order to be able to compete on world markets. The ever increasing environmental restrictions are mostly concerned with the emissions of ammonia and nitrate and the surplus of phosphorus on the mineral balance (Oenema, 1995). In order to manage this appropriately, the input of nutrients has to match as closely as possible the needs for forage production and the requirements of low emissions. This means that the input must equal the output in products plus unavoidable losses. For this purpose models are being developed, taking into account grass growth and regrowth, soil type, water level and available soil nitrogen throughout the growing season (Vellinga *et al.*, 1993).

The sources of nutrients are organic manure, fertilizers and biologically fixed nitrogen. The farmers will need to develop a sharp management in order to survive economically and to meet environmental restrictions. Farm management needs to be business-like and technological; nothing can be left to chance. Unfortunately, in such a scenario there will not be a place for white clover in permanent grasslands, because it is not possible to accurately regulate the amount of clover and therefore the amount of nitrogen in the system. Lucerne would be possible, because it is grown as a field crop. The amount of nitrogen it produces, which is nearly always mostly removed by cutting, can be easily calculated. "Organic" farming must rely on legumes for its nitrogen supply. As long as the proportion of the legume is not too large this will not cause problems, but it means that yields will be lower, at a maximum of 70% of that of farms using fertilizer and best technical means ('t Mannetje, 1991). By the way, it is a typical sign of Dutch policy makers' impotence that biologically fixed nitrogen on farms is not taken into account in the nitrogen balance for the calculation of the nitrogen surplus on farms. Once the biologically fixed nitrogen enters the grassland-animal system it acts in the same way as nitrogen from other sources and is equally subject to ammonia volatilisation and nitrate leaching ('t Mannetje and Jarvis, 1990).

Mixed farms are in a better position to meet environmental restrictions than specialized dairy farms, because they can produce forage crops which can replace concentrates, thus importing fewer nutrients into the farm. Preliminary figures from a small group of dairy farms in The Netherlands indicate that the nitrogen surplus increases with stocking rate. There is large variation between farms in nitrogen at the same stocking rate. At about 2.25 AU/ha there is a difference between farms of about 100 kg/ha. It will depend on the level of the allowable nitrogen surplus what will be a safe stocking rate to avoid having to pay large sums of penalty money for exceeding it. It is also clear that reduction in stocking rate can lead to a reduction in nitrogen surplus, so long as measures to reduce the surplus are taken. However, a lower stocking rate also means fewer dairy cattle, and less milk production per farm, unless more land will be purchased in order to keep a sufficiently large dairy herd for economic viability. Scenarios leading to lower yields per man and animal will not be economically sustainable, unless they will be subsidised, but governments prefer to reduce rather than increase subsidies.

Grasslands in the tropics

Of all the cattle in the world, 64% are kept in the tropics, of the buffaloes 100%, the sheep 51% and the goats 94%. However, the production of meat and milk in the tropics amounts to only 36 and 18% of the world production, respectively. This can be ascribed to poor nutrition, inadequate health care and management of animal production systems (Henzell and 't Mannetje, 1980).

Because of the continuing population growth and the increase in purchasing power in many tropical countries, there is an increasing demand for animal products, not only for food, but also for draft power and manure for crops and for fuel. Increasing food production in developing countries relies to a large extent on taking new land into production by further deforestation and cropping of rangelands. In order to halt this onslaught on the last areas of natural vegetation (forest and rangelands), it is necessary to increase production per unit area of already cropped land and grassland by intensification.

Grassland production can technically be increased by reducing degradation of rangelands and by pasture improvement using legumes, with minimal amounts of fertilizers and good management. Unfortunately, the adoption of measures for sustainable grassland improvement in many developing countries is seriously hindered by socio-economic constraints ('t Mannetje, 1996). Where these constraints play a less important role, grassland improvement with legumes can bring about large production increases. In Australia ('t Mannetje and Jones, 1990), Colombia (Lascano and Estrada, 1989), Brazil (Marashin and Jacques, 1993) and Costa Rica (Hernandez *et al.*, 1995), it has been shown that the carrying capacity of grassland for beef cattle can be quadrupled, whilst the production per animal can be increased 60%. This six-fold increase in production per hectare means that in a region, e.g. the Atlantic Zone of Costa Rica, only 25% of the grassland needs to be improved with a grass-legume mixture to double the total beef output of the region. This offers possibilities for other forms of land use, including reforestation or the production of tropical hardwood.

The chair of grassland science

The board of the sector Plant Production of the Wageningen Agricultural University proposed to combine the chairs of Field Crop Science for Temperate Climates and Grassland Science (temperate and tropical) . The University Council and the Board of the University gladly accepted it. Presumably this was meant to indicate that the two areas of science are closely related; more closely than other areas within plant production for which separate chairs have been maintained or created.

What is the case? There are two chairs in Plant Breeding and one and a half in Plant Production (one in Horticulture and the half in Field Crops now combined with Grassland). Is there a principal difference between plant production in horticulture (much of it in glasshouses) and that which takes place in the field?

I will not dwell further on the similarities and differences between areas of agronomic science, but it seems clear to me that there are bigger differences between grassland science and each one of the other plant production areas than between the two areas of plant production. With one chair for each of Plant Breeding, Crop Science and Grassland Science, the different aspects of agronomic sciences would have been better served and there would be one chair less than is the case now, amounting to a net saving. The only part of grassland science that fits well within Crop Science is forage production: the growth and quality of forage for animals. However, grassland ecology and the ecology and management of rangelands have nothing in common with Field Crop Science.

Conclusion

You will agree with me that grassland science does exist, but perhaps not that the Agricultural University will not be able to deal with it adequately. So be it.

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