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# Management options that increase herbage production in grassland-based livestock production systems

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**Abstract.** Herbage production is the most important measure of performance of grassland systems. Understanding how herbage production responds to various managements is crucial to the success of grassland systems, whether or not maximization of production is pursued. Most of the records of grassland production in the literature are taken as acceptable approximations of net herbage production. Analysis of these production records and accompanying quality data can generalize the response of grassland productivity and quality to individual managements, and can characterize the managements in terms of their efficiency and potential in increasing productivity and quality. Overall, maximum production response is ranked irrigation (11.2 t DM/ha) > nitrogen (N) fertilizer (9.8 t DM/ha) > legume mixture (5.2 t DM/ha) > phosphorus fertilizer (3.4 t DM/ha) > cutting frequency (2.5 t DM/ha) ≈ potassium fertilizer (2.4 t DM/ha) > cutting intensity (1.9 t DM/ha). Maximum response of herbage N concentration is greatest for N fertilizer (16 g/kg DM, for grasses) followed by legume mixture (14 g/kg DM), cutting frequency (8 g/kg DM) and cutting intensity (2 g/kg DM). Management of grassland systems for achieving a specified production and/or quality goal needs to consider different patterns of production and quality response to individual management inputs as well as other conditions (*e.g.* plant species, site conditions) involved in the systems.

**Keywords:** Biomass production, response to management, output/input efficiency, literature data.

## Introduction

Herbage production is the fundamental in grassland-based livestock production systems. The level of herbage production largely determines the number and performance of animals supported in the systems. A great deal of effort has therefore gone into establishing principles underlying grassland production and examining its responses to various biotic (*e.g.* plant species, sward structure) and abiotic (*e.g.* climate, soil nutrient and moisture) variables (*e.g.* Hopkins 2000; Parsons and Chapman 2000). Nevertheless, how grassland productivity can be increased by managements remains a major question in the operation of grassland systems.

The first half of this paper gives some background knowledge on herbage production in grass-lands. It covers conceptual, technical and phenolmenological aspects of the process. The second part explores potentials and limitations of major management practices as means of controlling herbage production. The analytical approach taken is a generalization based on global data which derive from 260 articles published in 52 international or domestic journals. Analysis is directed also to the efficiency and quality of production.

## Some background on herbage production

### *Tissue flows in the sward*

Herbage production is defined in 2 ways, in terms of tissue flows in the sward (Fig. 1). Gross herbage production ($P_{gross}$, also described as herbage growth) is the production of new shoot tissue by forage plants, derived as the gross canopy photosynthesis minus shoot respiration and minus the growth and respiration of below-ground tissue. New plant tissue produced as $P_{gross}$ is utilized as cut or grazed herbage ($U$, herbage utilization) or it enters a decomposition pathway as losses from senescence and death ($D$, tissue death), with the remainder contributing to net herbage accumulation ($\Delta M$, positive or negative):

$$P_{gross} = U + D + \Delta M \quad .....(1)$$

Net herbage production ($P_{net}$) refers to the production of shoot tissue that is not lost to senescence and death, and can be removed by mechanical harvesting or by animals under grazing:

$$P_{net} = P_{gross} - D \quad .....(2)$$

Combining Equations 1 and 2 gives:

$$P_{net} = U + \Delta M \quad .....(3)$$

All tissue flows, including the two measures of herbage production, are normally expressed as dry matter (DM) or organic matter (OM) weight per unit land area (g/m$^2$, kg/ha or t/ha) for a specified period of time (day, growing season, grazing season or year).

### *Measurement of herbage production*

Herbage production in grasslands is commonly quantified as the sum over a growing or grazing season of herbage yield (for mown swards; $\Sigma Y_i$ in Fig. 2) or herbage consumption (for grazed swards; $\Sigma C_i$ in Fig. 3). This method considerably underestimates gross herbage production, particularly in grazed swards, because it does

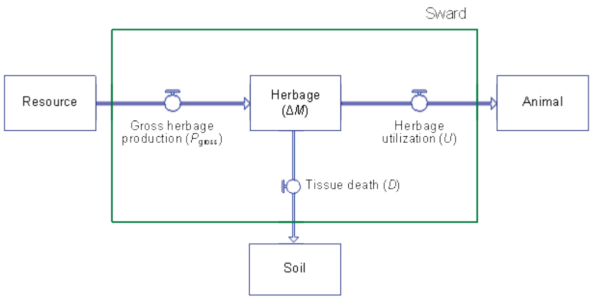


**Figure 1. Tissue flows in the sward. $P_{gross} = U + D + \Delta M$ and $P_{net} = P_{gross} - D = U + \Delta M$ where $\Delta M$ and $P_{net}$ represent net herbage accumulation and net herbage production, respectively.**

not take account of tissue death. Measurements on grazed swards show that tissue death is equivalent to 0.30–3.32 (mean = 1.10) times the rate of herbage consumption during a grazing season or year (Fukuyama *et al.* 1980; Parsons *et al.* 1983; Okajima *et al.* 1985). However, the method can reasonably estimate net herbage production because net herbage accumulation is usually negligible, compared to herbage utilization, over a sufficiently long period. Measurements on grazed and cut swards show that net herbage accumulation ranges between –0.11 and 0.12 times (mean = 0.02) the rate of herbage utilization during a growing or grazing season or a year (Fukuyama *et al.* 1980; Okajima *et al.* 1985; Hirata *et al.* 2003; Hirata unpublished data). Most published records of grassland production are thus taken as acceptable approximations of net herbage production, with a maximum bias (either way) of approximately 10%.

## *Factors affecting herbage production*

Herbage production in grasslands is affected by a number of environmental and biological factors (Table 1). Plant variables affect net herbage production as a consequence of their relatively direct effect on gross production and/or tissue death. For instance, the rate of tissue death in a sward increases in direct proportion to the mass of herbage maintained in the sward, whereas the rate of gross herbage production increases at a declining rate with herbage mass. As a result, the rate of net herbage production peaks at an intermediate level of herbage mass (Bircham and Hodgson 1983). Non-plant factors have an influence on herbage production through their effect on plant variables. For instance, animals influence plants directly through defoliation or indirectly via soil variables from excretion (defecation and urination) and trampling.

Managers can exercise control over grassland components to varying degrees (Table 1). Climatic conditions can only be partially controlled, by modification of microclimates through selecting sites with preferred conditions (*e.g.* selection of different slope aspects for radiation and soil temperature). Other components can be controlled more directly and to a better degree through management practices. Soil conditions can be altered through the use of fertilizers, liming, irrigation and drainage. Plant variables can be controlled through sowing, fertilizer application, defoliation, use of herbicides and irrigation. Animal variables can be changed through livestock management practices. Symbiotic microorganisms can also be manipulated through inoculation and/or sowing host plants.

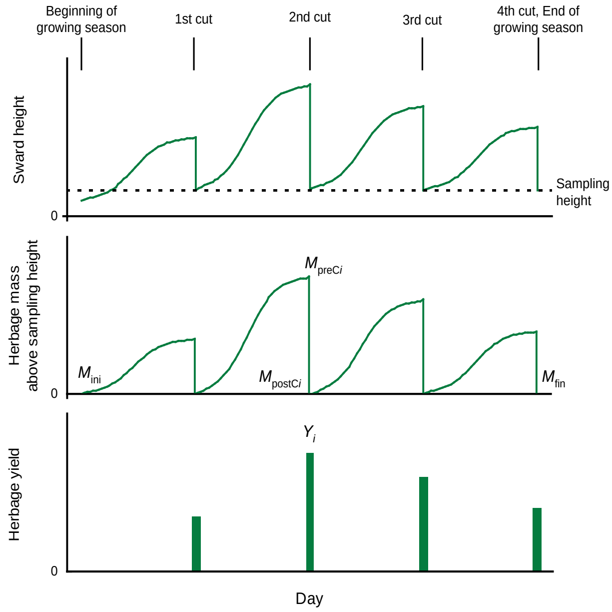


**Figure 2. Schematic representation of the changes in the sward height, herbage mass above the sampling height and herbage yield of a sward harvested mechanically (four times) to a consistent stubble height during the growing season. The sampling height is set at the stubble height. $M_{ini}$, herbage mass at the beginning of the growing season; $M_{fin}$, herbage mass at the end of the growing season; $M_{preCi}$, herbage mass before the *i*th cut; $M_{postCi}$, herbage mass after the *i*th cut; $Y_i$, herbage yield at the *i*th cut (*i* = 1, ..., 4). $M_{ini}$ is zero and $M_{fin}$ equals $M_{postC4}$ in this example. Because the sampling height equals the stubble height, $M_{postCi}$ equals zero and thus $Y_i$ is obtained as $M_{preCi}$.**

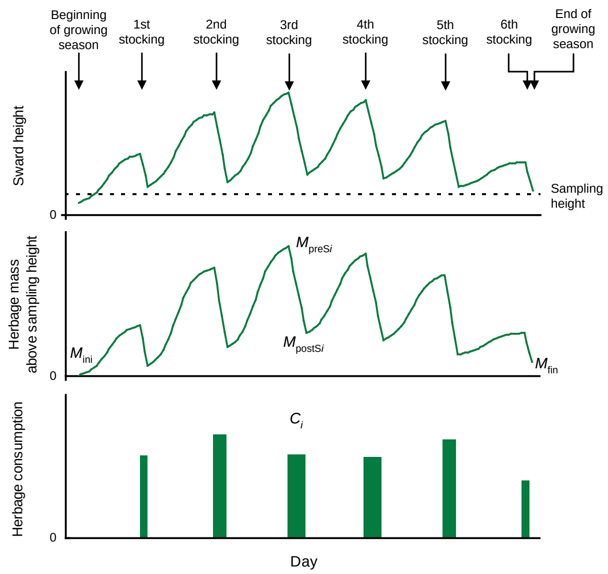


**Figure 3. Schematic representation of changes in sward height, herbage mass above the sampling height and herbage consumption of a sward stocked rotationally (6 times) to a variable height during the growing season. The sampling height is set below the grazing height. Mini and Mfin = herbage mass at the start and end of the growing season, respectively; MpreSi and MpostSi = herbage mass before and after the ith stocking period, respectively; and Ci = herbage consumption during the ith stocking period (i = 1–6). In this example Mini = 0 and Mfin = MpostS6. Ci is obtained as MpreSi – MpostSi + disturbed herbage accumulation during the ith stocking period.**

**Table 1. Major environmental and biological factors (components and variables) affecting herbage production in grassland systems and major methods of control which humans are able to exercise over the factors to control herbage production.**

| Component | Variable | Method of control |
|---|---|---|
| Climate | Temperature, radiation, rainfall | Selection of sites with preferred conditions |
| Soils | Mineral nutrients (macro and micro) | Fertilizer application |
| | Moisture | Irrigation, drainage |
| | pH | Liming |
| Plants | Species and botanical composition | Sowing, fertilizer application, defoliation, use of herbicides |
| | Canopy structure (height, mass, population density, leaf area) | Defoliation, fertilizer application |
| | Internal state (nutrients, water and reserves) | Fertilizer application, irrigation, defoliation |
| Grazing animals | Species, class (age, physiological state) | Selection of species and class |
| | Population density | Manipulation of stocking rate and stocking method |
| Symbiotic micro-organisms | Type (root nodule bacteria, mycorrhizal fungi, endophytes), species, frequency of infection | Inoculation, sowing host plants |
| Pests and diseases | Species, population density, frequency of infection | Use of pesticides, use of fungicides |

Partly from Pearson and Ison (1997).

## *Variation in herbage production*

The literature reports considerable variation in net herbage production from grasslands. For example, productivity of permanent grasslands in Europe ranges from 1.5–10 t DM/ha/yr at a regional scale (Smit *et al.* 2008). When published results from field trials across the world are synthesized, this variation increases to 0.3–71 t DM/ha/yr (Fig. 4–5). This range of values covers a wide variety of experimental conditions from no inputs (*e.g.* no fertilizer) to extremely high input (*e.g.* heavy fertilization), mostly in well-controlled small plots (usually < 30 $m^2$). High production records are thus regarded as potential outputs instead of farm-level performance. Average herbage production is higher for tropical species (10.2 t DM/ha/yr) than for temperate species (6.8 t DM/ha/yr) (Fig. 4), and is ranked grass–legume mixtures > grasses > legumes (9.4, 8.2 and 6.8 t DM/ha/yr, respectively; Fig. 5).

## *Herbage production in multiple criteria*

While herbage productivity is a crucial measure of the performance of a grassland system, herbage quality, efficiency and sustainability of production are equally important. Management that results in an increase in herbage production does not always favour these other criteria. For instance, applying fertilizers to increase herbage production may increase or decrease herbage quality through concentration or dilution of nutrients in shoot tissues. Efficiency in the use of inputs, such as fertilizers and irrigation, generally decreases as the level of production increases (Hopkins 2000). Decreasing fertilizer efficiency [specifically nitrogen (N)] enhances the risk of nutrient loss to the environment. Managing defoliation to maximize herbage production may involve the risk of decreasing growth potential and long-term sward sustainability, due to an accumulation of dead material and a reduction in plant recruitment (Hodgson 1990). Successful management of grassland systems is thus achieved by maximizing herbage production while ensuring quality, efficiency and sustainability of production. In addition, environmental issues or ecosystem services (*e.g.* water, nutrient and energy cycling and biodiversity) have become important in the management of grassland systems in recent years (Kemp and Michalk 2007). This aspect of grassland function is outside the scope of this paper.

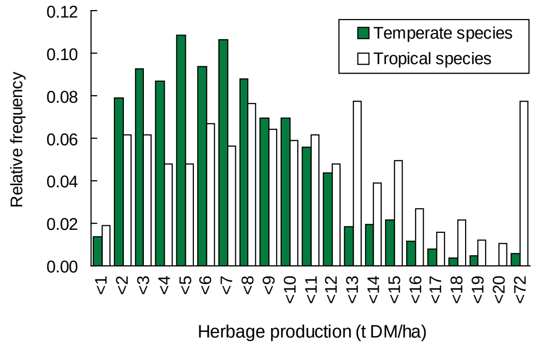


**Figure 4. Frequency distribution of herbage production in temperate and tropical species. Temperate species: *n* = 875, mean = 6.8, SD = 3.9; tropical species: *n* = 748, mean = 10.2, SD = 8.0.**

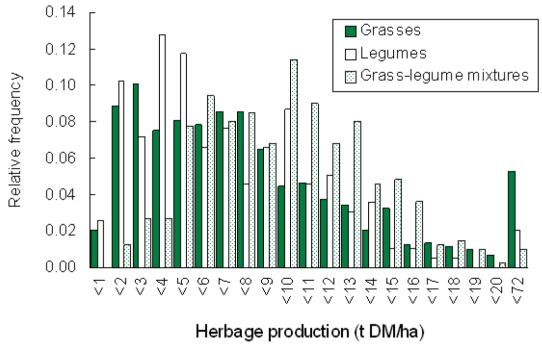


**Figure 5. Frequency distribution of herbage production in grasses, legumes and their mixtures. Grasses: *n* = 1051, mean = 8.2, SD = 7.3; legumes: *n* = 196, mean = 6.8, SD = 4.5; grass–legume mixtures: *n* = 413, mean = 9.4, SD = 4.0.**

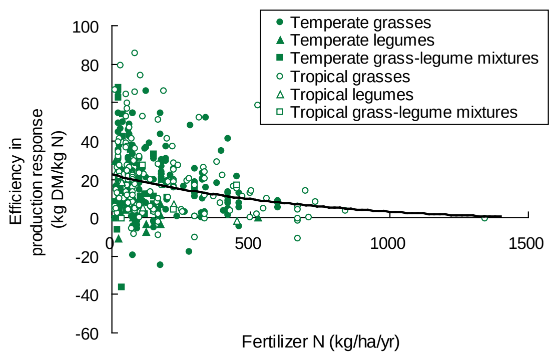


**Figure 6. Efficiency in herbage production response to fertilizer N plotted against fertilizer N rate. Trend line for all plant groups: y = –3.3 + 25.8exp(–0.0014x) [n = 397, $R^2$ = 0.053, P<0.001].**

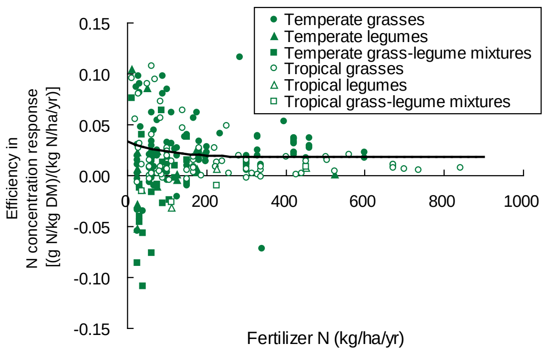


**Figure 7. Efficiency in herbage N concentration response to fertilizer N plotted against fertilizer N rate (n = 233). Trend line for grasses: y = 0.018 + 0.016exp(–0.0104x) [n = 188, $R^2$ = 0.023, P<0.05].**

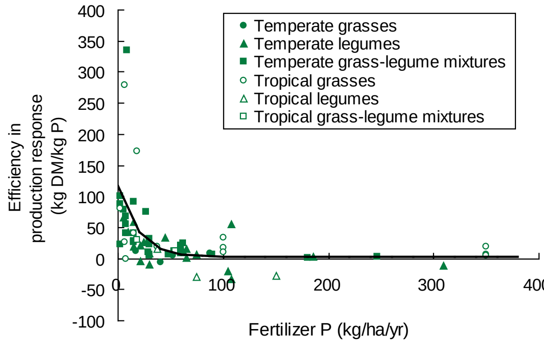


**Figure 8. Efficiency in herbage production response to fertilizer P plotted against fertilizer P rate. Trend line for all plant groups: *y* = 2.7 + 113.6exp(–0.0532*x*) [*n* = 69, $R^2$ = 0.290, P<0.001].**

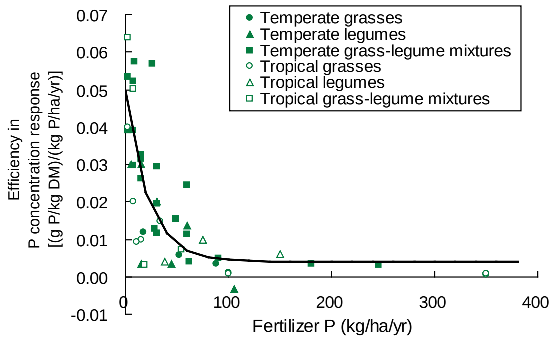


**Figure 9. Efficiency in herbage P concentration response to fertilizer P plotted against fertilizer P rate. Trend line for all plant groups: y = 0.004 + 0.045exp(–0.0451x) [n = 51, $R^2$ = 0.610, P<0.001].**

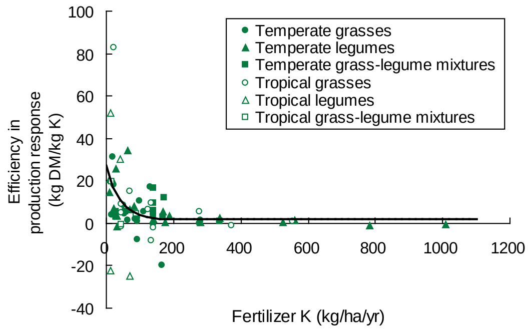


**Figure 10. Efficiency in herbage production response to fertilizer K plotted against fertilizer K rate. Trend line for all plant groups: *y* = 1.7 + 25.5exp(–0.0247*x*) [*n* = 71, $R^2$ = 0.173, P<0.001].**

## Management options for increasing herbage production

The response of herbage production to a management factor (*e.g.* fertilizer N) varies greatly, as a result of interactions with site conditions (climate, soil nutrient and moisture), plant type (species and cultivars) and levels of other management factors (*e.g.* fertilizer P and K, irrigation). Variation in grassland productivity across the literature is, therefore, only poorly or moderately explained by a regression equation with single factors as predictors. However, the regression line can be used to discover general trends in the effects of individual management options on herbage production. This is also the case for the efficiency and quality of production.

### *Nitrogen fertilizer application*

Nitrogen is essential for the formation of protein and is one of the major nutrients affecting herbage production. Data from N fertilization trials show great variation in the efficiency in herbage production response up to an application rate of ~400 kg N/ha/yr, including poor (small positive), nil and even negative responses (Fig. 6). Overall, the DM response for every kg N applied diminishes gradually as the rate of N is increased, indicating decreasing efficiency in plant use of fertilizer N. The trend line gives efficiencies of 22, 15, 10 and 3 kg DM/kg N at 0, 250, 500 and 1000 kg N/ha/yr, respectively, where the efficiency at 0 kg N/ha/yr equals the initial slope of the production response curve to fertilizer N. The efficiency in the response of herbage N concentration to fertilizer N is highly variable up to an application rate of ~200 kg N/ha/yr, ranging from concentration (positive responses; up to ~0.1 g N/kg DM per kg N/ha/yr) to dilution (negative responses; down to approximately –0.1 g N/kg DM per kg N/ha/yr) of N in shoot tissue (Fig. 7). It is noted that most of the negative responses derive from pure legumes and grass–legume mixtures. On average, efficiency declines gradually for grasses as the rate of N is increased, giving increases of 0.034, 0.027 and 0.02 g N/kg DM per unit N application (kg/ha/yr) at 0, 50 and >100 kg N/ha/yr, respectively. The efficiency at 0 kg N/ha/yr corresponds to the initial slope of the N concentration response curve to fertilizer

### *Phosphorus fertilizer application*

Phosphorus (P) plays a vital role in many chemical reactions (particularly for energy transfer) within plants and is a major element for growth. P fertilization experiments show that the rate of response in both herbage production and herbage P concentration to fertilizer P decreases steeply as P rate is increased (Fig. 8–9). This results in a sharp decline in efficiency of fertilizer P use. The trend lines give increases of 116, 11 and 3 kg DM/ha/yr and 0.05, 0.01 and 0.004 g P/kg DM per unit P application (kg/ha/yr) at 0, 50 and >100 kg P/ha/yr, respectively.

### *Potassium fertilizer application*

Potassium (K) plays a major role in plant metabolism and is essential for many plant functions (*e.g.* stomatal opening and closure) which are important for plant growth. Data from K fertilization trials demonstrate that the rate of

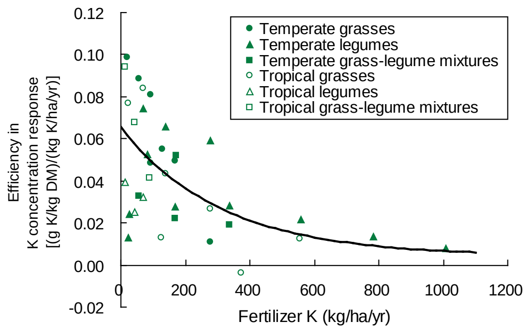


**Figure 11. Efficiency in herbage K concentration response to fertilizer K plotted against fertilizer K rate. Trend line for all plant groups: y = 0.004 + 0.061exp(–0.0032x) [n = 35, $R^2$ = 0.351, P<0.001].**

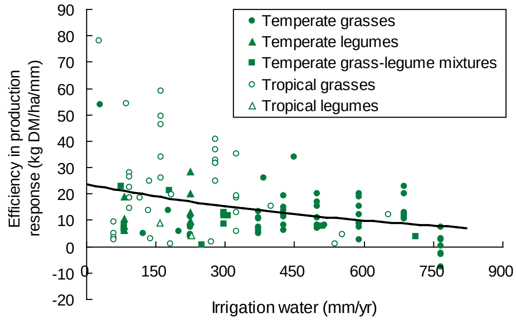


**Figure 12. Efficiency in herbage production response to irrigation plotted against irrigation amount. Trend line for all plant groups: *y* = 23.7exp(–0.0015*x*) [*n* = 119, $R^2$ = 0.111, P < 0.001].**

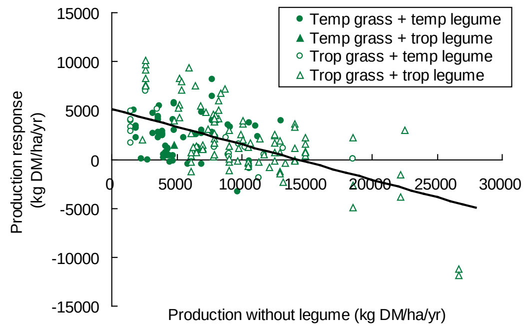


**Figure 13. Response of herbage production to legume addition plotted against production without legumes. Trend line for all plant groups: y = 5155 – 0.36x [n = 179, $R^2$ = 0.323, P<0.001].**

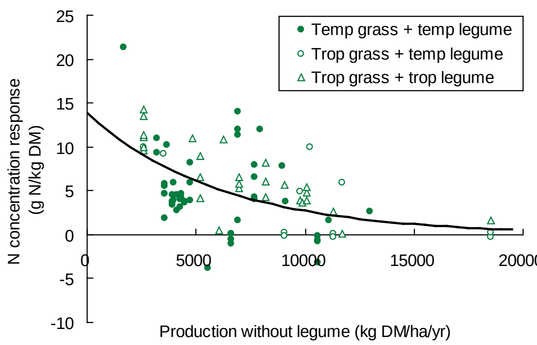


**Figure 14. Response of herbage N concentration to legume addition plotted against production without legumes. Trend line for all plant groups: *y* = 13.9exp(–0.00016*x*) [*n* = 86, $R^2$ = 0.270, P<0.001].**

response of herbage production and herbage K concentrate-ion to fertilizer K declines as the rate of K is increased, with decreasing efficiencies in the use of fertilizer K (Fig. 10–11). The trend lines give production efficiencies of 27, 9, 4 and 2 kg DM/kg K at 0, 50, 100 and 200 kg K/ha/yr, respectively, and K concentration increases of 0.07, 0.03, 0.02 and 0.01 g K/kg DM per unit K application (kg/ha/yr) at 0, 250, 500 and 1000 kg K/ha/yr, respectively.

### *Irrigation*

Plant available water has a significant effect on shoot growth, and is often a limiting factor for herbage product-ion in grasslands receiving low rainfall. Published experi-mental results show that irrigation increases herbage pro-duction to varying degrees with a tendency toward decreas-ing efficiency in response to increasing water levels (Fig. 12). The trend line gives water use efficiencies of 24, 16, 11 and 8 kg DM/ha/mm at 0, 250, 500 and 750 mm/yr, respectively.

### *Mixing legumes with grasses*

Legumes can obtain N through symbiotic fixation of atmospheric $N_2$ and transfer N to grasses in grass–legume communities. Data from mixed cultivation trials, however, show that the addition of legumes to a grass sward does not always favour grassland production (Fig. 13). Whether the addition of legumes increases or decreases herbage production depends on productivity of the grass swards without legumes. The response of herbage N concentration to legume addition in grass–legume mixtures declines as the productivity of grass swards increases (Fig. 14). The trend lines give responses of 5155, 3348, 1542 and –265 kg DM/ha/yr and 13.9, 6.1, 2.7 and 1.2 g N/kg DM when grass swards without legumes yield 0, 5000, 10000 and 15000 kg DM/ha/yr, respectively. The responses at 0 kg DM/ha/yr are taken as potentials with limited reliability, because mixing legumes with grasses of nil production cannot happen in reality and the response values derive from extrapolation beyond the range of data (particularly for N concentration). Overall, relatively high benefits to both quantity and quality can be expected when grass swards produce <10000 kg DM/ha/yr.

### *Defoliation*

Defoliation generally affects herbage productivity by affecting the leaf area and the quantity and activity of meristems remaining, the rate of photosynthesis per unit leaf area and the remobilization of reserve substances in the plants. It can influence herbage quality by changing the ratios of leaf/stem and young/aged tissues in the sward canopy. Frequency and intensity are two major parameters which define defoliation. Data from defoliation experi-ments indicate cutting frequency and intensity have similar effects on herbage productivity (Fig. 15), but cutting frequency has a greater impact on herbage quality (N and digestible dry matter (DDM)) than cutting intensity (Fig. 16–17). There is a negative correlation between the responses of herbage production and quality to cutting frequency (*r* = –0.617 for N and –0.437 for DDM, P<0.05; data not shown). This implies that a cutting frequency that results in a production increase reduces quality, and *vice versa*.

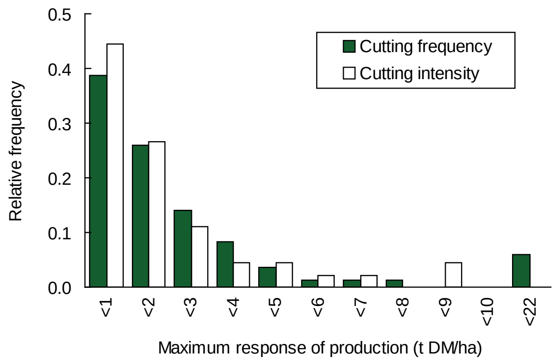


**Figure 15. Frequency distribution of maximum response of herbage production to frequency and intensity of cutting within individual trials. Cutting frequency: n = 85, mean = 2.5, SD = 3.8; cutting intensity: n = 45, mean = 1.9, SD = 2.1.**

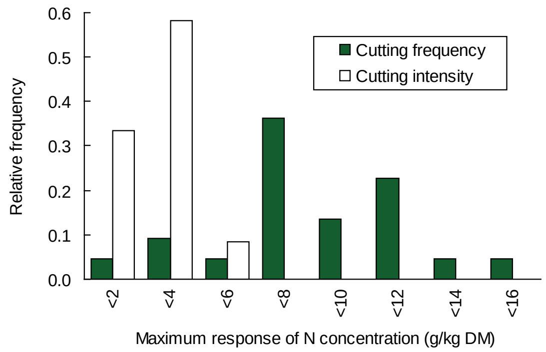


**Figure 16. Frequency distribution of maximum response of N concentration of herbage to frequency and intensity of cutting within individual trials. Cutting frequency: *n* = 22, mean = 8.1, SD = 3.5; cutting intensity: *n* = 12, mean = 2.3, SD = 1.3.**

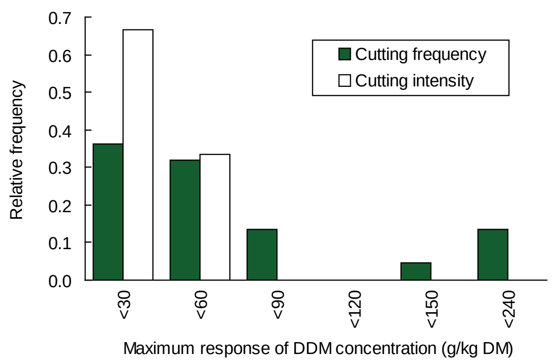


**Figure 17. Frequency distribution of maximum response of DDM concentration of herbage to frequency and intensity of cutting within individual trials. Cutting frequency: *n* = 22, mean = 58, SD = 61; cutting intensity: *n* = 12, mean = 22, SD = 17.**

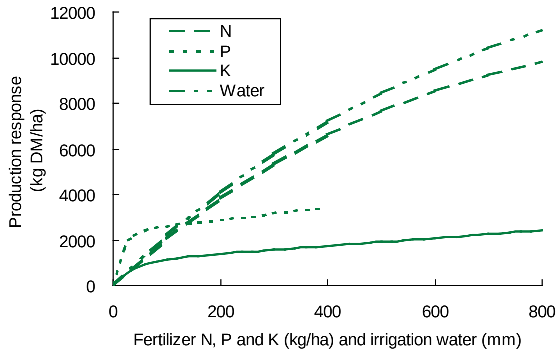


**Figure 18. Response of herbage production to fertilizer N, P and K and irrigation. Derived from trend lines in Figures 6, 8, 10 and 12.**

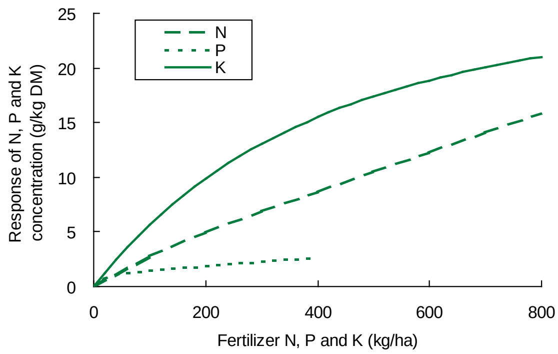


**Figure 19. Response of N, P and K concentration of herbage to fertilizer N, P and K. Derived from trend lines in Figures 7, 9 and 11. N response is for grasses.**

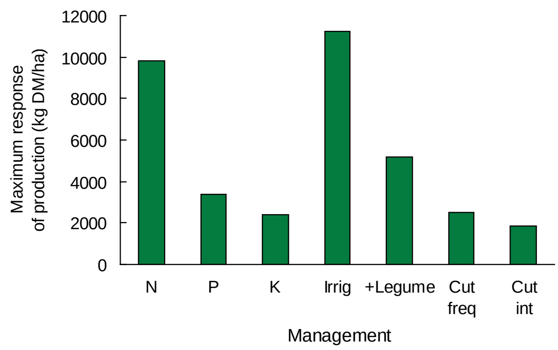


**Figure 20. Maximum response of herbage production to management factors. Derived from trend lines in Figures 6, 8, 10, 12 and 13, and means in Figure 15. The values for N, P and K fertilizer and irrigation are for inputs of 800 kg N, 400 kg P, 800 kg K per ha annually and 800 mm/yr, respectively.**

## *Comparative characterization of managements*

The comparative responses of herbage production and quality to different management factors are presented in Figures 18–21. Overall, applying N fertilizer consistently increases herbage production and results in higher N concentrations in grasses over a wide range of application rates (Fig. 18–19). By contrast, P fertilizer only increases herbage production and P concentration at application rates up to ~40 kg/ha/yr. Herbage K concentration increases over a wide range of K fertilizer rates (so-called luxury uptake), but produces poor herbage production responses. Irrigation results in increases in herbage production similar to N fertilizer. When all management factors examined in this study are considered together, their relative ranking of maximum herbage production responses is: irrigation > N fertilizer > legume mixture > P fertilizer > cutting frequency ≈ K fertilizer ≥ cutting intensity (Fig. 20). The maximum response of herbage N concentration is greatest for N fertilizer (for grasses), followed by legume mixture, cutting frequency and cutting intensity (Fig. 21).

The generalizations used in this analysis are a gross simplification of actual grasslands, where productivity and quality are influenced by multiple factors. The data sets available for response–management combinations have limitations of imbalanced derivation with respect to site

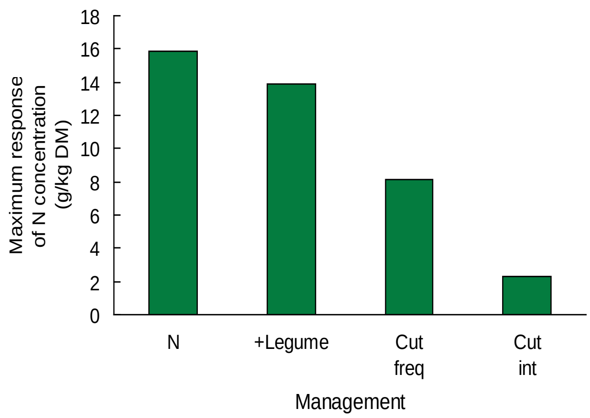


**Figure 21. Maximum response of herbage N concentration to management factors. Derived from trend lines in Figures 7 and 14, and means in Figure 16. The value for N fertilizer is for grasses with an input of 800 kg N/ha/yr.**

conditions, plant groups and management inputs. The trend lines (Fig. 6–14, 18–19) and the means (Fig. 15–17, 20–21), therefore, cannot accurately predict herbage production or quality responses for individual systems, which may be one reason why the generalization approach has not been used widely in the evaluation of management impacts on grasslands. However, this approach can provide new insights into the comparative responses of herbage production and quality to individual management factors under the multiplicity of factors involved.

## Conclusion

Understanding how herbage production responds to different management factors is crucial for better management of grasslands, irrespective of whether maximizing production is the goal. Most records of grassland production in the literature are regarded as acceptable approximations of net herbage production. Meta-analysis of these data and accompanying quality measurements can quantitatively generalize the response of herbage productivity and quality to management, despite the limitations of data availability and interactions with other variables. Individual management factors result in different patterns of grassland production and quality responses. This needs to be factored in, along with other variables (*e.g.* plant species and site conditions), when a particular management approach (type and amount of input) is considered for achieving a specified production and/or quality goal.

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