THE McCLYMONT LECTURE

THE APPLICATION OF GRAZING MANAGEMENT TO INCREASE SUSTAINABLE LIVESTOCK PRODUCTION

B.E. NORTON

Dept of Rangeland Resources, Utah State University, Logan, Utah, 84322-5230, USA

SUMMARY

Graziers and researchers have reached an impasse regarding the merits of rotational grazing systems that involve a large number of paddocks and short grazing periods. Most research trials have concluded that continuous grazing is either better or no worse than rotational grazing in terms of livestock production. Three reasons are offered to explain these results: (1) The paradigm underlying studies of rotational grazing, namely, that rotational grazing can control frequency of defoliation, is flawed. (2) Continuous grazing in large paddocks causes patch grazing and localized pasture degradation, but this aspect of continuous grazing has not been addressed in trials comparing grazing systems. (3) Continuous grazing in large paddocks creates very uneven distribution of livestock, but research trials have usually assumed spatial homogeneity in forage availability and utilization. The potential for significantly higher livestock production under a cell grazing system can be justified from scientific arguments using existing research data. The key to sustainability of cell grazing is very high stock density to reduce selectivity, and moderate utilization during grazing to maintain forage productivity. More even animal distribution is automatically achieved by such a system, and the benefit of this to livestock production is already evident from research studies involving small paddocks.

Keywords: rotational grazing, livestock production, distribution

INTRODUCTION

The divergence between theory and practice in the use of rotational grazing to enhance livestock production has widened in the past 20 years. The rotational grazing strategies which many producers claim are responsible for higher profits and better enterprise sustainability are the same kind which the research community has concluded can offer only marginal benefits to production and probably are not cost-effective.

Researchers have struggled for decades to test the value of rotational grazing systems against continuous grazing. The conceptual model underlying this research relies on the assumption that continuous grazing fails to protect desirable species from heavy, selective and destructive utilization, and that rotational grazing will solve that problem (Wheeler 1962), with the expectation that more forage would be available and livestock production enhanced, compared to pastures continuously grazed. But the results of grazing trials have been counter-intuitive. Just about every comprehensive review of rotational grazing research has found that the majority of studies conclude that continuous grazing is no worse than rotational grazing, or may even be preferable from a livestock production point of view (Wheeler 1960; Driscoll 1967; Herbel 1974; Gammon 1978a; Morley 1981; Valentine 1990; Heitschmidt and Taylor 1991). Whenever an economic assessment of rotational grazing has been attempted, continuous grazing was usually the recommended choice (eg Wilson *et al*. 1987; Hart *et al*. 1988; Heitschmidt *et al*. 1990b). Yet a significant number of graziers in several countries continue to claim that rotational grazing has been one of the keys to successful, profitable livestock production, the other keys being better record-keeping, better planning, and better business management in general, including the courage to be innovative and the wisdom to be adaptive.

No one argues that improved managerial skill will not create a more profitable enterprise, but we do debate whether we can substantially increase livestock production by changing the way we manage the relationship between forage resources and the livestock which exploit them. Thus far the research community, in the United States as well as Australia, has nothing to recommend except continuous grazing and conservative stocking. Graziers are dissatisfied with that, and are looking elsewhere for advice. This paper is an attempt to resolve this impasse. I will propose a theoretical argument which validates the practice of certain forms of rotational grazing. But in view of "the dichotomy between research results and practical experience" (McCosker 1994) it is not sufficient merely to show that substantially higher production from rotational grazing has a solid, science-based rationale; it is also necessary to explain why hundreds of grazing studies have arrived at a contrary conclusion. I do not believe that the research was poorly conducted, but I do suggest that the terms of reference were limited, leading to erroneous extrapolation of conclusions to a commercial livestock operation, and I think that the paradigm upon which the research enquiries were based may be flawed.

Some introductory comments are necessary to clarify concepts and terminology. Rotational grazing occurs in several different forms that were classified neatly by McCosker (1993) according to the number of paddocks involved and the speed of the rotation. Grazing strategies that require from two to seven paddocks demand grazing periods that last on the scale of a year, months or weeks, sometimes with heavy utilization towards the end of the period, and the rationale emphasizes the importance of rest periods to allow the vegetation to recover from grazing. Grazing strategies that involve 10 or more paddocks permit grazing periods as short as a few days, and the rationale stresses the avoidance of excessive defoliation combined with adequate rest. As the number of paddocks in the rotation increases, and the area occupied by the grazing herd decreases commensurately, the justification for such strategies includes reference to the value of high stock density impacts to the functional integrity of the resource. The particular class of rotational grazing practices that require at least 20, 30 or preferably more paddocks, and are characterised by quite short grazing periods, is the main subject of the current debate between scientists and graziers cited above, and thus the focus of this paper. In the popular literature this class is recognized by various names, including time control grazing, cell grazing, short duration grazing, mob stocking and block grazing, and is often placed within the managerial approach known as holistic resource management. As a matter of convenience, in this paper I shall use the term cell grazing (after Earl and Jones 1996), to cover the entire genre, and shall apply the term ‘grazing system’ to the management of grazing animals according to a set of principles or ideas implemented in an organized, rational fashion.

One cannot proceed very far on this topic without invoking the names of Savory and Parsons (1980) who, together with their students and colleagues, have successfully advocated the use of cell grazing among commercial producers as part of a management package which appears to have consistently increased livestock production and often reduced costs of operation in the United States, Australia and elsewhere. They have brought the issue of rotational grazing into the spotlight as graziers look for ways to remain in business in a worsening economic environment and ever-capricious climate. We should also acknowledge a debt to Voisin (1959) and Acocks (1966) who inspired people such as Savory (see Goodloe 1969) to explore the merits of rotational grazing in low-rainfall rangeland ecosystems using grazing periods that were unconventionally short, hence Savory’s initial designation of ‘short duration grazing’ (Savory 1978).

The analysis given in this paper would be superfluous if scientific attempts to test cell grazing had not generated results so contradictory to the experience of many commercial graziers, or if Savory, Parsons, and their colleagues had been able to provide a satisfactory theoretical basis for the grazing practices they advocate. Unfortunately, the collection of principles articulated thus far by proponents of cell grazing either fails to provide a cohesive body of testable theory (eg McCosker 1993), or else the evidence offered in support of the principles is anecdotal and data-free (eg Savory 1988) rather than objective and data-based. Before addressing cell grazing *per se*, I will consider the conundrum of why the benefit of rotational grazing could be so intuitively obvious and yet so difficult to demonstrate in research trials.

My discussion of these issues is in the context of rangeland ecosystems with relatively low rainfall (about 750 mm or less) that have strong seasonality and are liable to droughts, rather than more temperate pastures with higher, fairly reliable rainfall more evenly distributed through the year. In the context of eastern Australia, this would include the tablelands and land to the west.

A FLAWED PARADIGM

Both graziers and scientists have observed that paddocks which are continuously grazed tend to deteriorate. They concluded that continuous grazing at conservative stocking rates gives livestock maximum selectivity, which is expressed in heavy utilization of preferred, palatable species. Heavy grazing pressure on desirable species gives a competitive advantage to less desirable species or exotic weeds, which increase in the pasture at the expense of more palatable plants. Numerous clipping studies in the first half of the 20th century (reviewed by Jameson 1963) showed that repeated, frequent defoliation reduces forage yield. Experimenters presumed with confidence that their results demonstrated the problem with continuous grazing, and paid little attention to the fact that clipping and mowing are imprecise representations of defoliation by livestock. [Papers reporting the classic studies at Cambridge by Woodman and his team (Woodman *et al*. 1929, 1931; and Woodman and Norman 1932), are entitled “The influence of the intensity of grazing on the yield, composition and nutritive value of pasture herbage" even though the small subplots were mowed, not grazed.] Thus the body of experimental evidence from clipped plants or plots justified the argument that controlled grazing was needed to protect palatable plants from continuous exposure to herbivory. During an imposed rest period in the absence of livestock, the argument continues, the vigour of grazed plants will be restored and their ability to produce forage will be sustained. A critical corollary of this argument is that each grazing period should not be long enough to allow the herbivore to defoliate the regrowth of a tiller which had been grazed earlier in the same period. When translated into practice, these ideas become the foundation for rotational grazing, which, in addition to preserving the forage value of the grazed vegetation, presents livestock with fresh feed on a regular basis. The ideas have been in print, in English, for a long time, at least since Anderson's writings in the late 18th century (quoted by Johnstone-Wallace and Kennedy 1944, and by Voisin 1959).

The crux of the matter is the proposition that under continuous grazing plants are defoliated repeatedly and severely, but the data in direct support of that notion are relatively sparse. Even Voisin's textbook has no data on this issue. Instead, he asserts: "Without committing any great error, we can say that very short rest periods of 6 [to] 12 days...correspond more or less with what takes place in the case of 'continuous grazing' with cattle" (Voisin 1959, page 19). In the case of high-rainfall temperate pastures suited to dairy farming, Voisin's assumptions regarding continuous grazing may not be far off the mark, given high stocking rates and small paddocks. In lower-rainfall rangeland ecosystems, however, the frequency of defoliation under continuous grazing does not appear to be as severe as was assumed. A large fraction of plants or tillers are not touched at all, a small percentage are grazed twice, and relatively few receive three or more defoliations in a long grazing period (Gammon 1978b; Norton and Johnson 1981; Hart *et al*. 1993b).

It follows that if frequent and severe defoliation is not a problem with continuous grazing, then the implementation of rotational grazing should have little effect on defoliation frequency (Gammon 1984; Gammon and Twiddy 1990; Barnes and Denny 1991; Kirkman and Moore 1995). And that indeed appears to be the case. Working at the Matopos Research Station in Zimbabwe, Gammon (1978b) recorded minor differences in number of defoliations per tiller over a six-month period when he compared continuous grazing with a six-paddock rotation using a 12-day grazing period. There was a tendency for a higher percentage of tillers to be grazed twice under the rotation (28.2 vs. 21.8%, averaged over five species); only about 6% of all tillers were grazed three or four times. In two studies in Wyoming seven years apart, Hart *et al*. (1993b) found no difference between continuous grazing and an eight-paddock rotation in terms of frequency of defoliation for western wheatgrass grazed over a five-month grazing season. In one year of their study (1990) they recorded significantly more defoliations for blue grama continuously grazed, but only 12% of tillers were grazed twice under the heavy grazing treatment. Gammon and Twiddy (1990) in Natal could not find a difference in defoliation pattern between a four-paddock rotation involving 14-day grazing periods and an eight-paddock rotation with seven-day grazing periods. Gillen *et al*. (1990) obtained an average of only 52% of tillers defoliated per grazing period of three to seven days in an eight-paddock rotation stocked above the recommended level in Oklahoma. In a subsequent test of this rotation (Derner *et al*. 1994), frequency of tiller defoliation was significantly higher in the continuous-grazing treatment, but at the highest stocking rate 25% of tillers subjected to the rotation were either ungrazed or defoliated just once in 150 days. The difficulty of imposing a particular pattern of tiller defoliation by implementing a rotational grazing system was also demonstrated in Texas by Heitschmidt *et al*. (1990a). They looked at defoliation frequency in a ten-paddock rotation with two to four days of grazing stocked at twice the rate recommended for the region. In each of four consecutive grazing periods, more than half the tillers were not grazed at all, and only one of the five species being studied experienced a substantial proportion (40%) of tillers grazed three or four times over the four-month experimental period. Studies which include stocking rate comparisons invariably show higher defoliation frequencies at higher stocking rates, but the effect of the rotation *per se* on defoliation pattern is weak or absent, at least in the context of most experimental designs which employ four to eight paddocks in the rotation.

THE CONCLUSION FROM RESEARCH

Researchers have been trying to control, through grazing management, the periodicity and intensity of defoliation and, via optimal defoliation regimes, to increase forage production. Such increases have been elusive because, as noted above, rotational grazing has not substantially altered the pattern of defoliation. Not surprisingly, scientists have concluded that rotational grazing *per se* cannot be expected to increase forage production. The emphatic statement by Wilson is representative of the general view that "the use of grazing systems for the improvement of short-term animal production is specifically rejected" (Wilson 1984, page 222). A window allowing qualified endorsement of rotational grazing is left open with the suggestion that it may favour changes in the botanical composition of the vegetation which, in turn, could generate a pasture inherently more productive than its predecessor, or than a comparable pasture remaining under continuous grazing (Gammon 1978a). Similarly, rotational grazing has been proposed as a remedy for range deterioration (Kirkman and Moore 1995). Researchers have claimed that it will permit sustained stocking rates that would otherwise be deleterious in the long term (Wilson 1984), but the magnitude of the increase in forage production or stocking rate has been judged in the neighbourhood of 15 to 30% (McMeekan and Walshe 1963; Morley 1968; Tainton *et al*. 1977; Gammon 1984; Bryant *et al*. 1989), scarcely worth the effort of implementation. And whether a certain rotational grazing system is likely to achieve a desirable change in vegetation will be site-specific, depending on the species composition of the grazed vegetation, the relative tolerances of species to the combined stresses of defoliation and competition, and the number and kind(s) of livestock being manipulated. And that somewhat equivocal conclusion comprises the sum total of what rotational grazing research can tell us. Solving problems arising from poor animal distribution is, however, not part of this research portfolio.

THE MISREPRESENTATION OF CONTINUOUS GRAZING

Research studies of rotational grazing systems are carried out using small paddocks, usually less than 25 ha and often less than 5 ha each. Researchers generally use such a paddock for the control treatment, continuous grazing, to which the rotational grazing system will be compared. The intent is to mimic a large paddock on a commercial property, but in translation to the research context a critical aspect of continuous grazing is lost, namely, uneven utilization over the landscape. What the researchers are actually representing under experimental conditions is a landscape which has been divided up into many small paddocks, all of which are continuously grazed at similar stocking rate. Yet the conclusions from the research tend to be extrapolated to all pastoral situations, regardless of paddock size. The usual conclusion is that rotational grazing is no better than continuous grazing, and within the terms of reference of the studies, that is perfectly valid. But if the spatial dimension is taken into account, a different interpretation may emerge, as discussed in the following section.

When researchers use small paddocks which receive relatively uniform grazing impact, they eliminate from their studies the most harmful consequence of continuous grazing, namely, patch grazing. Livestock entering a virgin field will establish an initial pattern of use which becomes reinforced as the season progresses (Daines 1980; Ring *et al*. 1985). Animals are attracted to areas previously grazed (Willms *et al*. 1988; Fuls 1992b), enlarging them and creating new ones nearby. Patches grazed heavily one year are more likely to receive heavy utilization in subsequent years, and areas neglected by livestock one year are likely to receive little use again. Willms *et al*. (1988) found that the tendency for neglected areas to be perpetuated is stronger than the perpetuation of heavily grazed patches, and that the reinforcement of these patterns is more pronounced under lighter grazing pressures. The phenomenon of semi-permanent grazing mosaics means that the stocking rate on heavily grazed patches is *de facto* much higher than the intended stocking rate for the paddock as a whole (Suckling 1965; Kellner and Bosch 1992). Intensity of defoliation, especially in terms of frequency, increases as stocking rate increases (Briske and Stuth 1982; Hart *et al*. 1993b), and the deleterious effects of high stocking rate are manifest in the patches so affected, leading to localised changes in vegetation and soil which are not easily reversed. Overgrazed patches in Alberta lost 28% of the soil A horizon, the normally dominant perennial grasses were replaced and forage production was depressed by 35% (Willms *et al*. 1988). Grazed patches in South Africa had lost most of the A horizon, exhibited lower soil water content, less vegetative cover and a higher proportion of undesirable species, yet they continued to receive much heavier utilization by sheep than adjacent patches in better condition (Fuls 1992b). Grazed patches in Zimbabwe had higher annual variability in plant production than less-degraded sites, with almost no forage produced in drought years (MacDonald 1978). Resting such areas during a drought may not facilitate their recovery if the patch has deteriorated beyond a threshold condition; on the contrary, the patch size may expand even without further grazing (Fuls and Bosch 1991).

The expression of very uneven distribution of grazing, and the consequent development of relatively stable, degraded patches which receive far higher impacts than would be determined from average stocking rate calculations, is a serious detriment to the practice of continuous grazing. But this dimension to grazing management has been almost ignored when continuous grazing and rotational grazing are compared in experimental studies, which tend to be designed on the assumption of spatial homogeneity in forage availability and utilization. The reason may lie in the difficulty of accommodating spatial variability within the small size of research paddocks, but it is also a function of the paradigm which directed the research process, namely, the perception that rotational grazing should be used to control the level of defoliation experienced by individual plants, not the nature of grazing distribution across paddocks.

The neglect of spatial variability when large paddocks are continuously grazed can also slant a theoretical comparison of grazing systems towards unrealistic conclusions. A concept often employed for such comparisons is grazing pressure - the ratio of livestock demand for forage relative to the amount of forage available. Scientists usually assume that all the forage within a paddock fence is available to the grazing animals it contains, no matter how large the paddock may be. When Heitschmidt and Taylor (1991) compared various grazing systems using grazing pressure as the principal criterion, continuous grazing was judged superior to all rotational systems because the latter required paddock subdivision, which automatically created higher grazing pressure as a function of smaller paddocks having less total forage available. However, in order to preserve the superiority of continuous grazing in their analysis they had to make the assumption that paddock subdivision was not a distinguishing feature of rotational grazing! In the absence of any impediment to the free movement of livestock around the paddock, it may seem logical to define grazing pressure without spatial consideration, but that is nevertheless unrealistic for large paddocks. The amount of forage available to grazing animals is not only a function of the size of the paddock, but also of the ability of livestock to explore the landscape and to search parts of it at close quarters. In other words, the behavioural parameters of walking distance, locational preferences and time spent grazing determine the amount of forage to which an animal or herd has reasonable access, and which might therefore be considered "available" forage on a daily basis.

INCORPORATING THE SPATIAL DIMENSION

The small herd of animals in a continuously grazed paddock on a research station has no problem exploring the entire paddock at least once a day or more often. The estimation of available forage in the paddock can be expressed without spatial qualification because all of it is accessible, and the problem of uneven access to the forage resource, as exhibited by animals grazing a large paddock, is not an issue. Rotational grazing trials have been spatially neutral, with few exceptions (eg Walker and Heitschmidt 1986; Hacker *et al*. 1988; Walker *et al*. 1988; Hart *et al*. 1993a). Most research has wrestled with temporal variability in defoliation, but for a commercial enterprise spatial variability is equally important.

Uneven distribution of grazing in the form of predictable patterns of use is well documented for large paddocks (eg Hodder and Low 1978; Low *et al*. 1980; Orr 1980; Senft *et al*. 1985; Owens *et al*. 1991). A New Zealand study of sheep grazing a 850 ha paddock is a particularly dramatic example (Scott and Sutherland 1981). Ash *et al*. (1996) considered this phenomenon in terms of the difficulty of extrapolating stocking rate experiments from small-paddock studies to the large paddocks of a commercial operation. I would like to address the scale issue in terms of the extrapolation of rotational grazing studies conducted with small paddocks.

Livestock grazing a large paddock exhibit spatial patterns of repetitive use; by inference, as well as observation, they repeatedly neglect or lightly use some areas of the paddock. The larger the paddock, and the lower the stocking density, the greater the proportion of paddock area neglected. At a finer scale, heavily grazed patches occur within the preferred communities. Graziers need management strategies to minimise patch overgrazing and improve the utilization of undergrazed areas (Fuls 1992a). I believe that space management of livestock grazing is the principal key to increasing sustainable livestock production.

If there is a grazing management system which will exploit forage that is otherwise neglected by livestock, without detrimental consequences to the pasture or rangeland resource, such a system will, by definition, increase the carrying capacity of the land. As paddocks become smaller, the opportunity to improve the spatial efficiency of forage utilization increases, although uneven distribution of grazing may never be eliminated (Taylor *et al.* 1985). Grazing trials on research stations are usually carried out with relatively small paddocks, and frequently are conducted at, or include among their treatments, stocking rates which are higher than those recommended for the district. Unfortunately, most reports of rotational grazing studies fail to express their stocking rates in relation to levels recommended for commercial enterprises in the neighbourhood. Whenever the experimental stocking rate is given such a perspective, however, one often finds that much higher stocking rates can be sustained on the research station. I suggest that a large part of that higher carrying capacity is due to the smaller paddocks employed on the station. The examples of this phenomenon presented in Table 1 emphasize data from the continuous grazing treatment, if available, and ignore any differences between the grazing systems, if evident.

A strong tendency to adhere to the flawed paradigm of rotational grazing discussed earlier, and to neglect spatial considerations, is evident in published reports which show clearly that carrying capacity was substantially increased under the conditions of the experiment but omit any reference to this result in the conclusions (eg Smoliak 1960). Morley (1987) noted the discrepancy between performance in grazing studies on a research station and performance on graziers' properties and suggested that it may be due to the inherently better soils and greater uniformity of pastures found on research stations. His assertion was not accompanied by specific examples, however, and although site quality may be a confounding factor, the case is yet to be presented convincingly.

A SCIENTIFIC ARGUMENT FOR CELL GRAZING

The critical component of cell grazing is the concentration of grazing animals at high stock densities. The critical caveat is that utilization of forage is moderate, even though grazing pressure is high. If a grazier manages for these two factors, it follows that he must use small paddocks to achieve high stock density and employ relatively short grazing periods to prevent heavy utilization. If his overall stocking rate remains the same or rises modestly, the only way to implement these precepts in practice is by moving animals around a large number of paddocks, at least 30 and preferably more, that together form the 'cell' of one management unit. Because stock density is high in the paddock being grazed, utilization is spatially more even than would otherwise occur, and once the animals have moved through the entire cell, every part of the landscape is explored by livestock and access to forage is maximised.

This argument hinges on the importance of grazing at high stock densities, in which the vegetation experiences high grazing pressure for short periods. The advantage of high stock density is that it can eliminate, or at least substantially reduce, selectivity by grazing livestock. The goal is to spread defoliation across as many plants as possible. When this happens, species ceases to be the primary criterion for diet selection. There are a number of graziers who have observed that livestock in a grazing cell will consume species which they would not normally touch at lighter grazing pressures. People report that problem weeds have been reduced in this manner, and I have observed cattle grazing young brigalow. Can such anecdotes be backed up by research? Few research studies have attempted to include a treatment representing a cell of 30 or 50 paddocks; most research trials employed four to eight, perhaps up to 16 paddocks. However, a study in South Africa is particularly relevant. Fifty head of cattle were grazed for one to two days on less than 1 ha, with approximately one month between grazing events, at two sites of mixed grassland vegetation. From two years of data collection, O'Connor (1992) found that the likelihood that a plant would be grazed was principally a function of plant size and previous grazing. Species identity was not important; grazing selectivity was not primarily a matter of species selection. Kirby *et al.* (1986) observed that cattle in an eight-paddock short-duration grazing cell consumed a greater variety of species, at utilization above 10%, than cattle under continuous grazing. The unpalatable wiregrass (*Aristida ramosa*) can be depressed by short-term heavy grazing on native pastures in northern New South Wales (Lodge and Whalley 1985). Earl and Jones (1996) recorded less wiregrass in cell-grazed pastures compared to continuously grazed areas nearby. In the western US, Pierson and Scarnecchia (1987) observed more uniform tiller defoliation when 124 cow-calf pairs grazed 24 ha for 12 days, five times the normal stocking rate. Within six days 90% of all tillers had been grazed at least once, and by the end of 12 days 80% had been grazed at least twice and mean tiller height had been reduced by 60%. On the other hand, improved uniformity of utilization as stock density increased was rejected by Walker *et al*. (1989) in Texas, although they did not observe grazing impacts at a plant or tiller level.

The second major element articulated above is that utilization of a grazed paddock must be moderate, implying short grazing periods. In the cell management unit, the rest periods are automatically long (80 to 150 days) as a function of the number of small paddocks required to achieve high stock density. The grazing regime thus described, ie low defoliation frequency at moderate intensity, matches the one identified by clipping studies (Jameson 1963) as being most likely to maximize forage production. Twenty years ago Denny and Barnes (1977) published the results of a rotational grazing study in which the length of the grazing period varied from five to 10 or 20 days. At both high and low stocking rates, livestock production increased

Table 1. Examples of rotational grazing trials in which stocking rate (SR) was maintained at a substantially higher level than the rate recommended for the area, without damaging the productivity of the pasture (AU = animal unit of approx. 450 kg liveweight)

Location	Length of trial (years)	Paddock size (ha)	Final SR (per ha)	Experimental SR relative to the recommended level	Reference
Alberta	9	120	0.13 steers	after first 2 yr, SR increased 60% above recommended level; mean annual utilization still 20% below target	Smoliak 1960
New Zealand	15	<5.0	2.6 ewes	"no apparent deterioration over the 15 years of... carrying very much more than normally accepted SR."	Suckling 1965
Canberra	5	1.5	17 ewes	discussion of results implies SR at twice commercial level was maintained without detriment to pasture, despite 2 dry years during study	Morley *et al.* 1969
Zimbabwe	7	48.6	0.2 cow	SR increased 70% after first year, then by additional 20% after third year, without detriment to vegetation	Denny & Steyn 1977
Texas	20	240	0.17 AU	SR of cont. gr. paddock increased 60% via series of small increases over 20 yr in attempt to achieve 50% forage utilization	Kothmann *et al.* 1970; Heitschmidt *et al.* 1982
Alberta	35	32	7.5 AU	forage production and beef yield maintained with SR at 50% above recommended level	Willms *et al.* 1986
Zimbabwe	6	12	0.56 steer	SR maintained at 40% above level regarded as long-term optimum, without detriment to vegetation	Barnes & Denny 1991
Oklahoma	5	0.4	7.5 AU	SR maintained at least 50% above recommended level, without detriment to vegetation	Gillen *et al.* 1991
Wyoming	13	9	0.56 steer	SR at 70% above recommended level achieved forage utilization of only 50%	Hart *et al.* 1988; Manley *et al.* 1995, 1997

as grazing period became shorter and utilization was correspondingly less severe. Length of the grazing period appeared to have more effect than length of the rest period. The benefit to forage production of moderate utilization under short grazing periods was shown by Tainton *et al.* (1977) who discovered a consistent trend towards higher production as the grazing period was reduced from 20 to 10 and two days; the response to shorter grazing periods was greater than the response to longer rest periods, which varied from 20 to 60 days in their seven-year study.

The combined effect of the two critical factors on vegetation composition is as follows. Reduced species selectivity brought about by high stock density imposes some defoliation pressure on species which do not usually experience utilization, which tend to be the less palatable species, and may place them at a competitive disadvantage relative to species accustomed to defoliation. The moderate utilization, even of palatable species, during short grazing periods preserves the vigour of desirable species. The long rest periods allow the increase or persistence of plants which are particularly sensitive to grazing, such as *Themeda triandra* (O'Connor 1997), causing species diversity to be maintained or increase.

I have been deliberately non-specific about the appropriate number of paddocks, the length of the grazing period and the consequential length of the rest period. Those details must be determined out for an individual situation. Nevertheless, the rationale for cell grazing given here emphasizes high grazing pressure to achieve non-selective grazing (in contrast to high utilization to achieve non-selective grazing, as proposed by Booysen 1969). Stocking densities should be 30 to 50 times higher than overall stocking rate. In order for grazing pressures to be high enough to accomplish this, and avoid heavy utilization at the same time, grazing periods of one to three days in 30 or more paddocks should be the goal. The cost of fencing necessary to implement the number of paddocks required by such a scheme would have been prohibitive 20 years ago, but with the current use of electric fencing that is no longer a serious constraint.

The potential defoliation of regrowth within the same grazing period is no longer a relevant issue when a cell is operating with large numbers of paddocks and short grazing periods. Also, this discussion of cell grazing has paid little attention to varying the length of the grazing and rest periods according to season. Many proponents of cell grazing have argued that time control is critical, and years ago Wheeler recommended, in the light of his thorough review of rotational grazing, that "the rest periods [in a rotation] should as far as possible vary according to the rate of regrowth, providing that some objective means of deciding when to move stock can be found" (Wheeler 1962, page 6). There is an established rationale for using shorter grazing periods and a faster rotation during the growing season (eg Voisin 1959). However, I suspect that the relative importance of time control declines as the number of paddocks in the cell increases. Time control may be important only in the transitional phase in the progression from a dozen paddocks or so, grazed selectively at moderate grazing pressure, to a large number of paddocks that can be grazed at high grazing pressure. In the former case, a small number of paddocks implies longer grazing periods during which the selective grazing pressure on the most palatable species can be damaging, and only careful monitoring of grazing impacts on those desirable species, coupled with timely movement of livestock out of the paddock, can prevent resource deterioration.

A FAMILY OF PRODUCTION CURVES

The preceding discussion explains how cell grazing can achieve substantial increases in overall stocking rate without damaging the productivity of the forage resource base. Most of that increase comes from improved management of animal distribution, but grazing at high stock density for short periods to achieve non-selective grazing at moderate intensity of defoliation is equally important. This paper would not be complete, however, without an attempt to reconcile grazier reports of higher productivity under cell grazing with the well-known relationship between animal production and stocking rate presented by Jones and Sandland (1974).

Graziers claim that production per head can be maintained at the higher stocking rate permitted under a cell grazing system. The Jones and Sandland model suggests that this is impossible; it states that rising stocking rate is always associated with decline in production per head, unless there has been a change in the productivity of the forage base. This model has been so widely cited by animal scientists, pasture agronomists and range scientists, that it has come to represent a framework which sets the boundaries within which all livestock managers must operate. We need to remember, however, that the model was developed from the results of a collection of research studies and suffers, like them, from a lack of consideration of the spatial dimension in commercial livestock operations. If grazing management can effectively increase the amount of forage to which the livestock herd has access through better animal distribution, then the old rules of the Jones and Sandland model no longer apply. A new line must be drawn based on greater available forage. Similarly, as Jones hypothesized in the 1987 Stobbs Memorial Lecture (Jones 1988), the slope of the linear relationship between animal production and stocking rate can change as a result of pasture improvement. If a grazing system achieves non-selective grazing, the species composition is likely to shift in favour of palatable species tolerant of defoliation, and such a pasture improvement would also warrant a revision of the animal production curve. Figure 1 illustrates a family of curves based on the original relationship depicted by Jones and Sandland. The animal production lines have the same y-intercept on the assumption that at very low stocking rates animals can select an optimum diet from a narrow range of similar vegetation types. The primary determinant of the intercept on the x-axis is quantity of forage available for consumption. As rotational grazing management increases forage availability via better animal distribution, while quality of forage offered to animals entering a paddock remains similar to the continuously grazed alternative, the slope of the livestock production line flattens out, and the changed circumstances justify horizontal movement to a new line which describes equivalent production per head at a higher stocking rate, and thus greater production per hectare. Thus Figure 1 represents a family of curves defined by spatial efficiency of forage utilization.

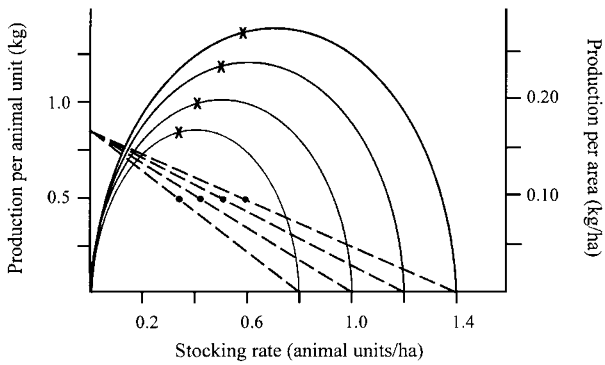

Figure 1. A family of curves illustrating increase in carrying capacity (equivalent production per animal at higher stocking rates) with increasing spatial efficiency of forage utilization. The linear relationships (- - -) show production per head on a scale of 0.85 to zero; the quadratic curves show the corresponding production per hectare. As a livestock enterprise moves from continuous grazing in large paddocks to rotational grazing systems with increasing numbers of small paddocks, the production per head travels horizontally from point to point on the dotted lines, and the corresponding production per hectare moves from one 'x' to another on the area productivity curves.

SUSTAINABILITY OF LIVESTOCK PRODUCTION DURING DROUGHT

Australian livestock production systems are characterized by high variability of rainfall. In the dry heartland, the incidence of years particularly favourable to forage production may govern the overall viability of stations with relatively low capital investment per animal unit and an opportunistic strategy for marketing animal production. Under more intensive management and higher rainfall, however, drought years are often the primary determinant of sustainability. The amelioration of depressed livestock production during drought, or a reduction in dependency on purchased feed during drought, or enhanced ability to carry animals through a drought without severe damage to the vegetation and soil resources, can be decisive to drought survival. Is there any evidence that cell grazing might improve the ability of a livestock operation to withstand the vicissitudes of drought? By definition, droughts are associated with substantially less water than average in the soil profile, either for particular seasons or throughout the year. It follows that plants with deeper root systems, or with more dispersed root systems, can better explore the soil volume and extract the limited water available. I submit that a system of grazing management which fosters greater root biomass and penetration than an alternative system, will realize better forage production and higher survival of desirable forage species under drought conditions.

Research studies that have examined the effect of defoliation on perennial-grass root systems have found that root biomass (or density) and rooting depth decline as (1) a greater proportion of leaf material is removed (Cook *et al*. 1958; Singh and Mall 1976; Hodgkinson and Baas Becking 1977; Stroud *et al*. 1985), especially during the growing season (Ganskopp 1988; Engel *et al*. 1998); or (2) the interval between defoliation events declines (Harradine and Whalley 1981; Motazedian and Sharrow 1987; Danckwerts and Nel 1989); or (3) simply as a function of long-term grazing impacts in general (Weaver 1950; Tomanek and Albertson 1957; Schuster 1964; Blydenstein 1966). Therefore, rotational grazing management which favours long rest periods between grazing events and tries to minimize severity of defoliation will ensure that, for a given stocking rate, the root systems of preferred forage species explore the greatest volume of soil. Cell grazing encourages high stock density for periods short enough that defoliation remains moderate. The implementation of this strategy requires large numbers of paddocks, which enforces a long interval (eg 80 days or more) between grazing periods. Thus defoliated plants under cell grazing management are likely to have a deeper root system with more biomass than defoliated plants under alternative grazing management which allows either more frequent use or heavier use. This should translate into more tolerance of drought conditions for cell-grazed forage species. Of course, repeatedly ungrazed plants under any management strategy will likely have maximum root biomass and penetration depth, despite occasional evidence to the contrary (eg Manley *et al*. 1995). For commercial livestock production, however, grazing management which permits extensive neglect of forage species is counterproductive; the goal is to obtain some forage value from as many plants as possible, in a sustainable fashion.

The obverse of the potential for improving drought survival via grazing management is the potential for exacerbating negative drought impacts via grazing management. Grazing practices which facilitate the kind of patch degradation described earlier in this paper will increase the grazing pressure on desirable plants already weakened by heavy use. As a result, desirable plants die out in overgrazed patches during droughts, and less desirable species or invading weeds occupy the vacated space, from where they may expand into the surrounding vegetation. Continuous grazing in large paddocks is usually associated with patch grazing and resource deterioration in localised areas.

Another facet to the sustainability of grazed vegetation during drought is the level of species diversity. As noted previously, cell grazing attempts to reduce selective defoliation pressure and spread grazing impacts across as many species in the vegetation as possible. The likely outcome is an increase in species diversity, as Earl (personal communication) found for cell-grazed sites in New England. There are two benefits to higher species diversity, both related to the fact that the phenologies of species in mixed vegetation generally do not overlap. First, there is more chance that at least some species in the vegetation will be in a phenological stage appropriate to a growth response to whatever rainfall comes during the normal growing season in a drought year. Second, the ‘rolling’ phenologies provide a temporal sequence of peak productions among the forage species present, and the availability of high-quality forage is spread out over a longer time span. The latter phenomenon is an advantage to livestock grazing mixed vegetation whether or not there is a drought (Ash *et al*. 1996).

To the prospect for sustainable increases in livestock production due to cell grazing we must now add the possibility that cell grazing minimizes the effects of drought. Although it may not prevent the need to reduce stock numbers in a severe and prolonged drought, it should at least postpone that reduction and could even lessen its magnitude.

REFERENCES

ACOCKS, J.P.H. (1966). *Proc. Grassld Soc. Sth. Afr.* 1, 33-39.
ASH, A.J. and STAFFORD SMITH, D.M. (1996). *Rangel. J.* **18**, 216-243.
BARNES, D.L. and DENNY, R.P. (1991). *J. Grassl. Soc. South. Afr.* **8**, 168-173.
BLYDENSTEIN, J. (1966). *J. Range Manage.* **19**, 93-95.
BOOYSEN, P.de V. (1969). *Proc. Grassld. Soc. Sth. Afr.* **4**, 84-91.
BRISKE, D.D. and STUTH, J.W. (1982). *J. Range Manage.* **35**, 511-514.

BRYANT, F.C., DAHL, B.E., PETTIT, R.D. and BRITTON, C.M. (1989). *J. Soil Water Conserv*. **44**, 290-296.
COOK, C.W., STODDART, L.A. and KINSINGER, F.E. (1958). *Ecol. Monogr*. **28**, 237-272.
DAINES, T. (1980). *Proc. Grassld Soc. Sth. Afr.* **15**, 185-188.
DANCKWERTS, J.E. and NEL, L.O. (1989). *J. Grassl. Soc. South. Afr.* **6**, 32-36.
DENNY, R.P. and BARNES, D.L. (1977). *Rhod. J. Agric. Res.* **15**, 129-142.
DENNY, R.P. and STEYN, J.S.H. (1977). *Rhod. J. Agric. Res.* **15**, 119-127.
DERNER, J.D., GILLEN, R.L., McCOLLUM, F.T. and TATE, K.W. (1994). *J. Range Manage.* **47**, 220-225.
DRISCOLL, R.S. (1967). *USDA For. Serv. Agric. Inform.* Bull. No. 315.
EARL, J.M. and JONES, C.E. (1996). *Rangel. J.* **18**, 327-350.
ENGEL, R.K., NICHOLS, J.T., DODD, J.L. and BRUMMER, J.E. (1998). *J. Range Manage.* **51**, 42-46.
FULS, E.R. (1992a). *J. Arid Envir.* **22**, 191-193.
FULS, E.R. (1992b). *J. Arid Envir.* **23**, 59-69.
FULS, E.R. and BOSCH, O.J.H. (1991). *J. Arid Envir.* **21**, 13-20.
GAMMON, D.M. (1978a). *Proc. Grassld. Soc. Sth. Afr.* **13**, 75-82.
GAMMON, D.M. (1978b). *Proc. First Inter. Rangeld. Congr.*, Denver, pp. 603-605.
GAMMON, D.M. (1984). *Zimbabwe Agric. J.* **81**, 59-64.
GAMMON, D.W. and TWIDDY, D.R. (1990). *J. Grassl. Soc. South. Afr.* **7**, 29-35.
GANSKOPP, D. (1988). *J. Range Manage.* **41**, 472-476.
GILLEN, R.L., McCOLLUM, F.T. and BRUMMER, J.E. (1990). *J. Range Manage.* **43**, 95-99.
GILLEN, R.L., McCOLLUM F.T., HODGES, M.E., BRUMMER, J.E. and TATE, K.W. (1991). *J. Range Manage.* **44**, 124- 128.
GOODLOE, S. (1969). *J. Range Manage.* B, 369-373.
HACKER, R.B., NORTON, B.E., OWENS, M.K. and FRYE, D.O. (1988). *J. Range Manage.* **41**, 73-78.
HARRADINE, A.R. and WHALLEY, R.D.B. (1981). *Aust. J. Agric. Res.* **32**, 565-574.
HART, R.H., BISSIO, J., SAMUEL, M.J. and WAGGONER, J.W. (1993a). J. Range Manage. **46**: 81-87.
HART, R.H., CLAPP, S. and TEST, P.S. (1993b). *J. Range Manage.* **46**, 122-126.
HART, R.H., SAMUEL, M.J., TEST, P.S. and SMITH, M.A. (1988) *J. Range Manage.* **41**, 282-286.
HEITSCHMIDT, R.K., BRISKE, D.D. and PRICE, D.L. (1990a). *Grass For. Sci.* **45**, 215-222.
HEITSCHMIDT, R.K., CONNER, J.R., CANON, S.K., PINCHAK, W.E., WALKER, J.W. and DOWHOWER, S.L. (1990b). *J. Prod. Agric.* B, 92-99.
HEITSCHMIDT, R.K., KOTHMANN, M.M. and RAWLINS, W.J. (1982). *J. Range Manage.* **35**, 204-210.
HEITSCHMIDT, R.K. and TAYLOR, C.A. (1991) *In* 'Grazing Management, An Ecological Perspective'. (Eds R.K. Heitschmidt and J.W. Stuth) pp. 161-177. (Timber Press: Oregon).
HERBEL, C.H. (1974). Plant Morphogenesis as the Basis for Scienntific Management of Range Resources. USDA Misc. Pub. 1271, pp. 138-149.
HODDER, R.M. and LOW, W.A. (1978). *Aust. Rangel. J.* **1**, 95-105.
HODGKINSON, K.C. and BAAS BECKING, H.G. (1977). *Aust. J. Agric. Res.* **29**, 31-42.
HOLSCHER, C.E. (1945) *Ecology* **26**, 148-156.
JAMESON, D.A. (1963). *Bot. Rev.* **29**, 332-394.
JOHNSTONE-WALLACE, D.B. and KENNEDY, K. (1944) *J. Agric. Sci., Camb.* **34**, 190-197.
JONES, R.J. (1988). *Trop. Grassl.* **22**, 97-115.
JONES, R.J. and SANDLAND, R.L. (1974). *J. Agric. Sci., Camb.* **83**, 335-342.
KELLNER, K. and BOSCH, O.J.H. (1992) *J. Arid Envir.* **22**, 99-105.
KIRBY, D.R., PESSIN, M.F. and CLAMBEY, G.K. (1986). *J. Range Manage.* **39**, 496-500.
KIRKMAN, K.P. and MOORE, A. (1995). *Afr. J. Range For. Sci.* **12**, 135-144.
KOTHMANN, M.M., MATHIS, G.W., MARION, P.T. and WALDRIP, W.J. (1970). *Texas Agric. Exp. Sta.* Bull. B-1100.
LOW, W.A., MULLER, W.J. and DUDZINSKI, M.L. (1980). *Aust. Rangel. J.* **2**, 76-82.
LODGE, G.M. and WHALLEY, R.D.B. (1985). *Aust. Rangel J.* **7**, 6-16.
MACDONALD, I.A.W. (1978). *Proc. Grassld Soc. Sth. Afr.* **13**, 103-109.
McCOSKER, T. (1993) Proc. 3rd Nat. Conf. of the Beef Impr. Assoc. of Austr., pp. 87-95.

McCOSKER, T. (1994) *Aust. Rural Sci. Ann.* 1994, pp. 26-31.
MANLEY, J.T., SCHUMAN, G.E., REEDER, J.D. and HART, R.H. (1995). *J. Soil Water Conserv.* **50**, 294-298.
MANLEY, W.A., HART, R.J., SAMUEL, M.J., SMITH, M.A., WAGGONER, J.W. and MANLEY, J.T. (1997). *J. Range Manage.* **50**, 638-646.
McMEEKAN, C.P. and WALSHE, M.J. (1963). *J. Agric. Sci., Camb.* **61**, 147-163.
MORLEY, F.H.W. (1968). *Aust. J. Exp. Agric. Anim. Husb.* **8**, 40-45.
MORLEY, F.H.W. (1981). *In* 'Grazing Animals' (Ed F.H.W. Morley) pp. 379-400. (Elsevier Sci. Publ. Co.: Amsterdam).
MORLEY, F.H.W. (1987). *In* 'Temperate Pastures: their production, use and management' (Eds J.L. Wheeler, C.J. Pearson and G.E. Robards) pp. 571-579. (CSIRO: Melbourne).
MORLEY, F.H.W., BENNET, D. and McKINNEY, G.T. (1969). *Aust. J. Exp. Agric. Anim. Husb.* **9**, 74-84.
MOTAZEDIAN, I. And SHARROW, S.H. (1987). *J. Range Manage.* **40**, 232-236.
NORTON, B.E. and JOHNSON, P.S. (1981). *Proc. XIV Intern. Grassld Congr.,* pp. 462-464. (Westview Press: Colorado).
O'CONNOR, T.G. (1992). *J. Grassl. Soc. South. Afr.* **9**, 97-104.
O'CONNOR, T.G. (1997). *Afr. J. Range For. Sci.* **14**, 7-11.
ORR, D.M. (1980). *Aust. J. Agric. Res.* **31**, 797-806.
OWENS, M.K., LAUNCHBAUGH, K.L. and HOLLOWAY, J.W. (1991). *J. Range Manage.* **44**, 118-123.
PIERSON, F.D. and SCARNECCHIA, D.L. (1987). *J. Range Manage.* **40**, 228-232.
RING, C.R, NICHOLSON, R.A. and LAUNCHBAUGH, J.L. (1985). *J. Range Manage.* **38**, 51-55.
SAVORY, A. (1978). *Proc. First Intern. Rangeld Congr.*, Denver, pp. 555-557.
SAVORY, A. (1988). 'Holistic Resource Management.' (Island Press: Washington DC).
SAVORY, A. and PARSONS, S.D. (1980). *Rangelands* **2**, 234-237.
SCHUSTER, J.L. (1964). *Ecology* **45**, 63-70.
SCOTT, D. and SUTHERLAND, B.L. (1981). *NZ J. Exper. Agric.* **9**, 1-9.
SENFT, R.L., RITTENHOUSE, L.R. and WOODMANSEE, R.G. (1985). *J. Range Manage.* **38**, 82-87.
SMOLIAK, S. (1960). *J. Range Manage.* **13**, 239-243.
SINGH, V.P. and MALL, L.P. (1976). *J. Range Manage.* **29**, 135-137.
STROUD, D.O., HART, R.H., SAMUEL, M.J. and RODGERS, J.D. (1984). *J. Range Manage.* **38**, 103-108.
SUCKLING, F.E.T. (1965) *Proc. NZ Grassld Assoc.* **26**, 137-152.
TAINTON, N.M., BOOYSEN, P. de V. and NASH, R.C. (1977). *Proc. Grassld Soc. Sth. Afr.* **12**, 103-104.
TAYLOR, J.A., HEDGES, D.A. and WHALLEY, R.D.B. (1985). *Aust. J. Agric. Res.* **36**, 315-325.
TOMANEK, G.W. and ALBERTSON, F.W. (1957). *Ecol. Monogr.* **27**, 267-281.
VALENTINE, J.F. (1990). 'Grazing Management'. (Academic Press, San Diego: California).
VOISIN, A. (1959). 'Grass Productivity.' (Crosby Lockwood & Sons Ltd.: London).
WALKER, J.W. and HEITSCHMIDT, R.K. (1986). *J. Range Manage.* **39**, 428-431.
WALKER, J.W., HEITSCHMIDT, R.K. and DOWHOWER, S.L. (1989). *J. Range Manage.* **42**, 143-148.
WEAVER, J.E. (1950). *J. Range Manage.* **3**, 100-113.
WHEELER, J.L. (1960). CSIRO Plant Industry Div. Rep. No. 20.
WHEELER, J.L. (1962). *Herb. Abstr.* **32**, 1-7.
WILLMS, W.D., DORMAAR, J.F. and SCHAALJE, G.B. (1988). *J. Range Manage.* **41**, 503-508.
WILLMS, W.D., SMOLIAK, S. and SCHAALJE, G.B. (1986). *J. Range Manage.* **39**, 182-187.
WILSON, A.D. (1984). *in* 'Rangelands: A Resource Under Siege'. (Eds P.J. Joss, P.W. Lynch and O.B. Wiliams) pp. 221-225. (Austr. Acad. Sci.: Canberra).
WILSON, P.N., RAY, D.E. and RUYLE, G.B. (1987). *J. Range Manage.* **40**, 401-404.
WOODMAN, H.E., NORMAN, D.B. and BEE, W. (1929). *J. Agric. Sci., Camb.* **19**, 236-265.
WOODMAN, H.E., NORMAN,D.B., and FRENCH, M.H. (1931). *J. Agric. Sci., Camb.* **21**, 267-323.
WOODMAN, H.E., and NORMAN, D.B. (1932). *J. Agric. Sci., Camb.* **22**, 852-873.