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The water environment and implications for productivity

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Abstract. Water deficits constrain productivity of herbivores on savanna grassland in two ways. The lack of soil water in the dry season causes a nutritional stress due to the low protein concentration and low dry matter digestibility of dead tropical perennial grass tissue. Less frequently, lack of rain in the growing season causes feed shortages in the subsequent dry season. The first part of this paper deals with simulation of these effects using weather data and describing the variation which occurs in northern Australia.

Options for reducing the impact of the annual dry season include sowing a pasture legume, since dry legume leaf is relatively nutritious. The second part of the paper examines variation imposed by the water climate on legume production potential and on the risk of spoilage due to out-of-season rainfall.

Thirdly, the paper examines the effects of nitrogen and phosphorus deficiencies and the consequences of mismanagement of the soil surface on the water constraint.

It is concluded that the substantial progress in reducing nutritional stress of the annual dry season has changed the nature of the problem of periodic droughts. Whereas formerly the main impact of nutritional stress was high cattle mortalities, now genetically better adapted cattle survive by consuming a greater proportion of the low-quality herbage with the aid of mineral supplements. The sowing of legumes increases average carrying capacity and increased pasture utilization.

Both innovations increase the risk of overgrazing in years of below-average pasture production. Avoidance of accelerated land degradation as a result of loss of buffering capacity inherent to the former extensive system will require skilful management.

Key words. Savanna, climate, animal nutrition, intensification, stability, northern Australia.

INTRODUCTION

Water deficiencies are a major determinant of the productivity of savanna vegetation and of any replacement vegetation. However, nitrogen and phosphorus deficiencies are at least equally important. Operationally, an important distinction is that it is feasible to supply nitrogen and/or phosphorus; however, when this is done, the importance of water as a constraint increases. This paper attempts to examine the water constraint in relation to the productivity of the economically most important producer of the Australian savanna – the beef animal. It looks first at constraints in the system where cattle graze native grassland and then at the modification where nutritional deficiencies are reduced by introduction of a pasture legume and P by supplementation or fertilization. In both cases four questions are asked: How does the water environment constrain cattle productivity? How can the effects be quantified using weather data? How does this constraint vary in time and space? and What are the options for management?

THE NATIVE GRASSLAND

A characteristic of the savanna is the long dry season which constrains animal production in every year; during this period, nutritional value of grass falls below maintenance requirements. Natural grass herbage in Australian tropical savannas is, in the main, highly sclerophyllous. Only young leaf has sufficient protein concentration and sufficiently high digestibility to support weight gain of cattle. This means that active pasture growth is a prerequisite for animal growth and couples animal growth closely to soil water supply. Fig. 1 shows the decline in diet quality and weight gains with decline in growth index (G.I.).

G.I. is defined as the ratio of growth rate under current environmental conditions to optimum growth rate and was calculated as the product of a water balanced-derived moisture index and a thermal index as per Fitzpatrick & Nix (1970). Using data on live weight changes and weather, G.I. has been calibrated to reflect pasture quality (McCown, 1980). In Fig. 1 it is evident that cattle began to lose weight when the G.I. dropped to approximately 0.1

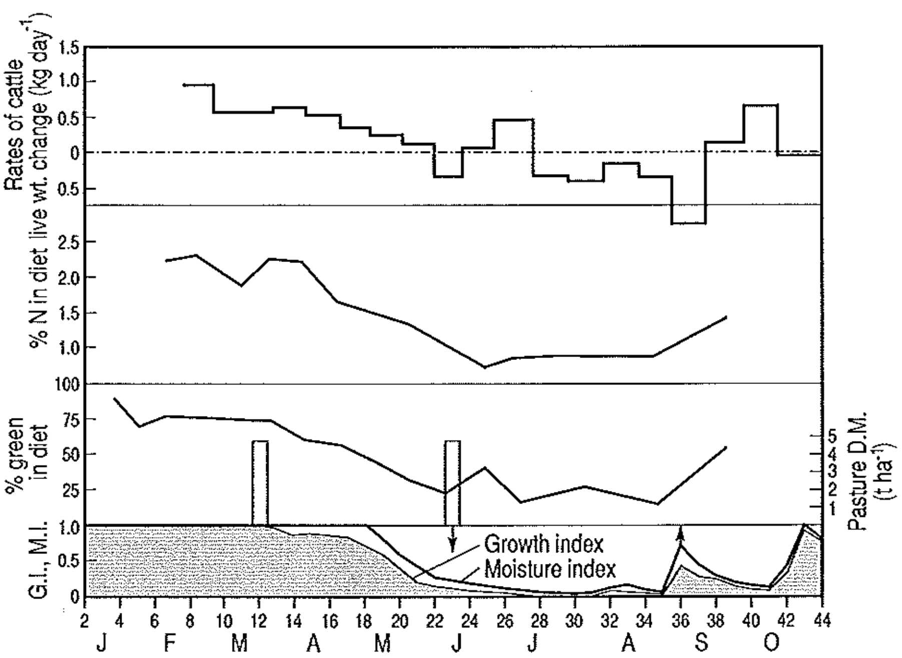

FIG. 1. Trends in liveweight, diet attributes, pasture yield, and pasture environment of cattle grazing native pastures near Woodstock, Queensland. (Liveweight and %N data from Hunter, Siebert & Breen, 1976; remaining data, McCown, unpublished.)

and, in the main, lost weight until rain in September caused a substantial new growth period. McCown (1980) used this point as the termination of a 'green season' (STOPWK) and the start of the 'dry season'. The initiation of green season, the main weight gain period, was found to coincide with a sequence of 8 weeks in which G.I. is greater than 0.1 for three of four and six of the eight weeks GOWK. (The event in Fig. 1 just barely qualifies as the start of the green season.) In this paper, 'green' and 'dry' seasons so defined will appear as Green Season and Dry Season and durations as Green Weeks and Dry Weeks.

Diet quality during a given week was classified as being either high enough to support liveweight gain (a Green Week) or not (a Dry Week). Variation in liveweight change among years or stations was explained by variation in number of Green Weeks or Dry Weeks. McCown *et al.* (1981a) found Dry Weeks in the Dry Season to account for 75% of variation in liveweight loss in the dry season and the relationship is approximated by the 'greater than 15' curve in Fig. 2.

Whereas water deficits limit production via diet quality in every year, drought years occur only periodically. In these years insufficient rainfall in the Green Season results in a shortage of feed in the dry season. Dry matter production can be predicted using the G.I.

For a specified vegetation–phenological stage–soil fertility situation, some maximum increment in dry matter production can be expected during a week with G.I. = 1.0.

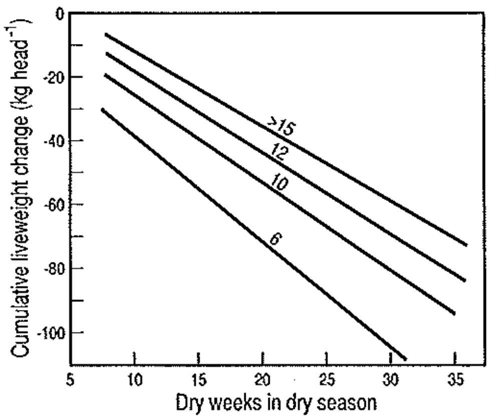

FIG. 2. The dependency of liveweight loss in the dry season on length of the dry season as influenced by Growth Weeks in the Green Season. (Generalized from McCown *et al.*, 1981a.)

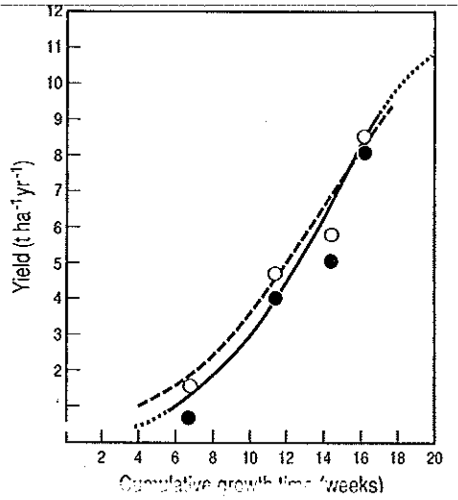

FIG. 3. Production of tropical legume swards as a function of Growth Weeks. (○, Total yield of *Stylosanthes humilis*-dominated swards (McCown, 1973); ●, yield of pure *Stylosanthes hamata* (Williams & Gardener, 1984).)

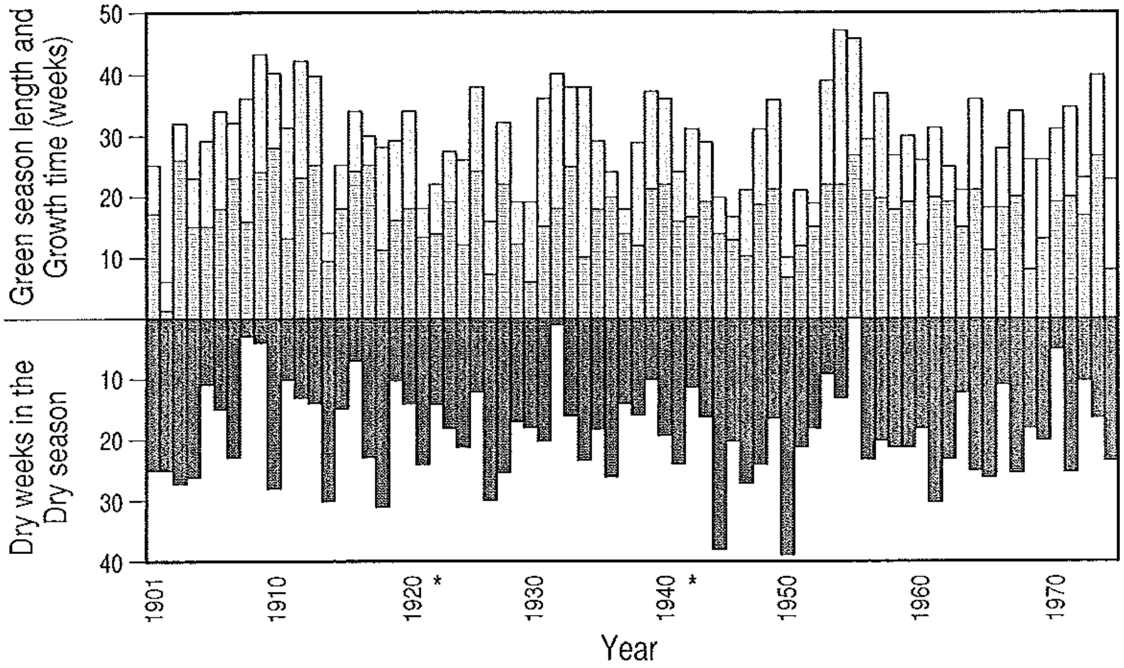

FIG. 4. Variation in simulated lengths of Dry Seasons, Green Seasons and Growth Weeks at Woodstock, Queensland.

Whereas 2 weeks at G.I. = 1.0 should produce twice as much, 2 weeks at G.I. = 0.5 might be expected to produce an amount equivalent to 1 week at G.I. = 1.0 (Williams & Gardener, 1984). This suggested a simple independent variable that combines the 'goodness' of conditions for growth and the duration at that level of 'goodness'. The 'growth time' (weeks or days) has proved valuable in being readily integrated over any real time period, and in the ease of interpretation of cumulative values by comparison to the real time duration, i.e. the maximum growth time, had conditions been optimum. (Williams & Probert (1983) set out a theoretical analysis which demonstrates a functional relationship between dry matter production and the growth time as determined by water and temperature regime.) A great deal of the variation in dry matter production among years and sites due to variation in rainfall and soil water storage capacity can be explained by relating production to a growth time variable (Fig. 3). This variable should relate closely to carrying capacity and should explain variation in cattle performance when herbage quantity is limiting.

In the data used by McCown *et al.* (1981a), there were years in which *quantity* effects on liveweight loss could be distinguished from low *quality* effects. Losses in the dry season in years in which Growth Weeks are greater than 15 are linearly related to Dry Weeks in the dry season, whereas larger losses occurred when Growth Weeks are less than 15 especially at high stocking rates (Fig. 2).

Mott *et al.* (1986) used this approach to compare the herbage productivity of six major savanna types in Australia. They found a close relationship between vegetation types, productivity, and the Growth Index.

With two variables that relate individually to forage quantity and quality (i.e. Growth Weeks and Dry Weeks), and having shown how they are derived from standard climatic data, it is possible to estimate how cattle performance varies, both from year to year and from place to place. Variation among years for growth weeks, the duration of the Green Season (potential Growth Weeks), and Dry Weeks in the Dry Season are shown for Woodstock, Queensland, for a 72-year period in Fig. 4. Year-to-year variation is high. Using generalized relationships from Fig. 2, liveweight loss for each year can be estimated. The resulting frequency distribution of losses is shown in Fig. 5. Variation among years for Katherine is low by comparison (Fig. 5). In seven years in 100, winter rainfall at Woodstock, representing the Townsville–Burdekin region, is sufficient to actually enable weight gain in the dry season, whereas cattle at Katherine would be expected to always lose at least 10 kg. At Woodstock, six years in 100 have low green season production (few Growth Weeks) preceding a long dry season, resulting in more than 80 kg loss. At Katherine this did not occur in the thirty-four years analysed.

Geographic and temporal variation in annual Growth Weeks, Green Weeks and Dry Weeks has been described using eighty stations with an average rainfall record of 40 years (McCown, 1982).

Increased production in the northern beef industry requires reduction of the close dependency of protein supply on green feed supply. One approach has been to feed non-protein nitrogen supplements in the dry season which result in increased intake of desiccated, low quality, perennial grass tissue. Because digestibility of this herbage remains low, production responses are modest; however, because the costs are relatively low and cattle mortality is greatly reduced, this practice has been widely adopted.

An approach with a greater potential to increase production is replacement (or supplementation) of native grasses with plants less sclerophyllic, and consequently, with more nutritious mature leaves. Introduced grasses,

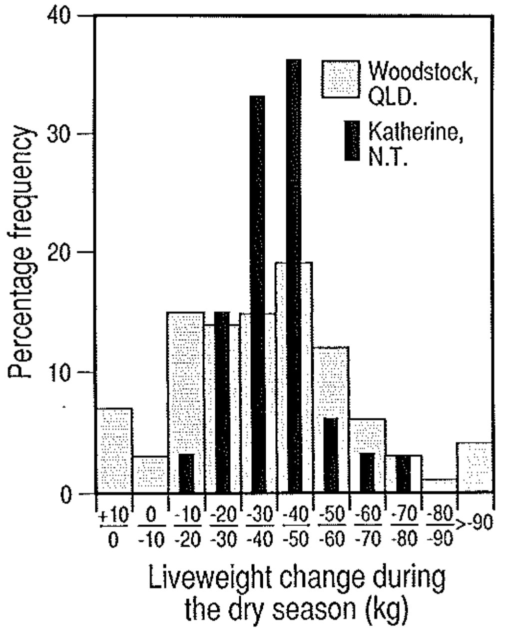

FIG. 5. A comparison of frequences of simulated Dry Season liveweight losses at two stations with similar mean annual rainfalls.

mainly from Africa, provide this to some degree, but these grasses have higher requirements of N and P than native grasses. Because legumes have much higher dry season nutritive value than any grasses but also fix their own nitrogen, most of the research on improved pastures in northern Australia has focused on finding and assessing legumes adapted to this climate. Several legumes, mainly in the genus Stylosanthes, have been found to grow and persist well (Edye, 1987). One of the most successful of these is Caribbean stylo (*Stylosanthes hamata* cv. Verano) which is shown in Fig. 6.

SOWN LEGUME-GRASS PASTURES

How does the water environment influence productivity on these pastures?

Climatically-induced variation in pasture legume production potential has been described by Williams & Gardener (1984) and by Williams & Probert (1983) using the methods outlined earlier for calculating growth time and relating this to dry matter production of Caribbean stylo. The cumulative probability-yield functions for Caribbean stylo with P non-limiting for a range of sites are shown in Fig. 7. The contrast between the Townsville–Burdekin sites of Pentland and Woodstock and that of Katherine is marked. The highly variable plant production at Pentland and Woodstock which is characteristic of the Townsville–Burdekin region is in strong contrast to the more reliable climate of Katherine which is representative of the more strongly monsoonal areas of northern Australia.

The means by which pasture legumes contribute to dry season nutrition of cattle differ. One group, currently typified by Caribbean Stylo, sheds leaf readily as the soil dries. Dry leaf, while less nutritious than green leaf, is much more nutritious than mature grass leaf, and cattle lick leaf litter from the ground. A second group, typified by Shrubby stylo (*S. scabra*) retains leaf in a greens state for much of the dry season even though growth is negligible.

FIG. 6. An example of Caribbean stylo (*Stylosanthes hamata* cv. Verano) in the dry season showing edible leaf litter. A legume which has been found to grow and persist well in the wetter regions of the Australian savanna.

The respective efficacies of the 'dry leaf strategy' versus the 'green leaf strategy' depend strongly on dry season rainfall and evaporation. Rain following leaf shed results in microbiological spoilage and decline in nutritive value and acceptability to cattle (Norman, 1967; McCown, Wall & Harrison, 1981b). Rain prior to leaf shed serves to prolong the period of green leaf retention. A recent study quantifies the geographic and temporal variation in dry season weather with regard to the dry leaf strategy (Wall & McCown, 1989). Fig. 8 shows the large variation among regions in the average contribution of legume in alleviating the 'nutritional drought'. In the far northern locations spoilage is of minor importance, and indeed much of the impetus for pasture legume research came from demonstration of the success of this strategy at Katherine (Station 7) (Norman, 1967).

Elsewhere, especially in the Townsville–Burdekin region, the average proportion of the dry season before spoilage occurs is modest. Fig. 9 shows the differences between the cumulative probabilities of having periods of sound legume greater than a given number of weeks for Katherine and Woodstock. Whereas at Katherine more than 18 weeks of sound legume can be expected in eight of ten years, at Woodstock, the same can be expected in only two in ten. Although in general, it can be presumed that the places least suited for a dry leaf strategy are better suited for a green leaf strategy, some areas appear to be poorly

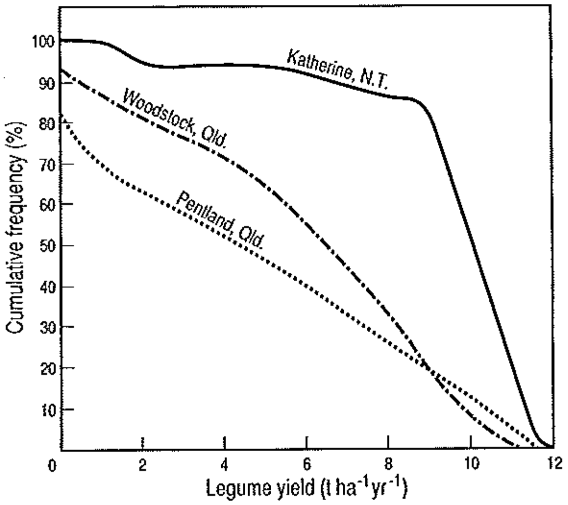

FIG. 7. Cumulative frequencies of *Stylosanthes hamata* cv. Verano yield at three stations. (From Williams & Probert, 1983.)

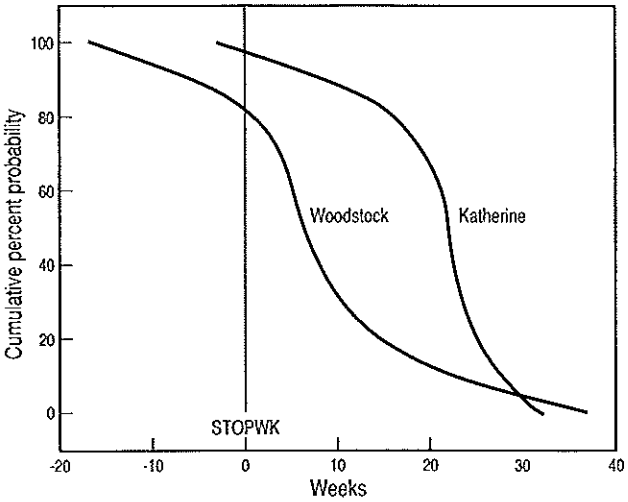

FIG. 9. Probability of exceeding a specified value of the time from the end of the Green Season of native grass pasture (STOPWK) until dry legume spoilage occurs.

endowed to support either reliably. In the Townsville–Burdekin and the West Kimberly regions, dry seasons are not dry enough for good dry legume preservation, but are often too long and dry for the strongly perennial legumes to make sufficient contribution of green leaf.

NON-CLIMATIC INFLUENCES ON THE WATER CONSTRAINT TO PRODUCTIVITY

Although savanna environments are usually characterized on the basis of the severity of the water constraint, any discussion of management of productivity of savannas without consideration of mineral nutrient constraints would be artificial. In the studies reviewed by Mott *et al.* (1986), the native pasture production potential predicted by their climatic analysis was often greater than measured herbage biomass production (Fig. 10). The potential production was estimated by computing the growth time which is not constrained by temperature, water or nutrient and multiplying this time by the potential growth rate of the grass species under conditions where nutrients are non-limiting.

The shortfall is most apparent on the massive sesquioxidic soils (Isbell, 1983) represented by the

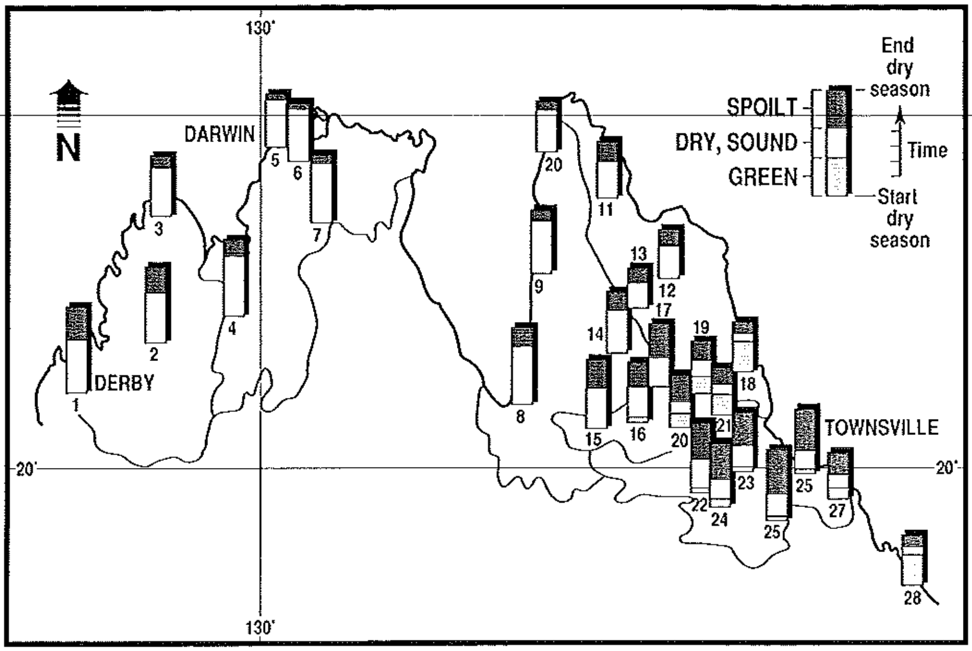

FIG. 8. Simulated states of leaf during the Dry Season at twenty-eight stations in northern Australia (mean length of Dry Season, mean times for which leaf is green, dry and sound, and spoilt). (From Wall & McCown, 1989.)

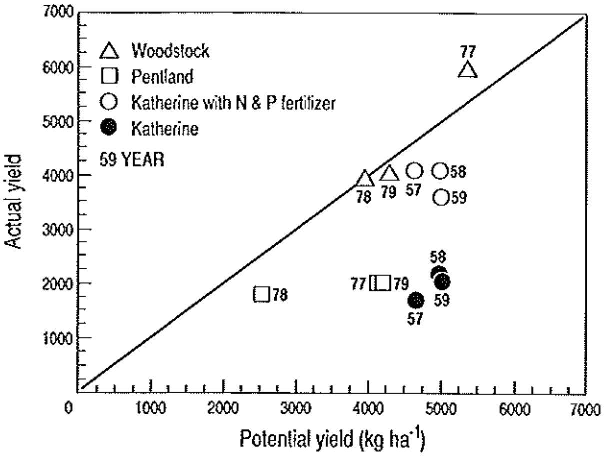

FIG. 10. Actual yield of native grass pastures versus simulated yield in years indicated, assuming nutrients non-limiting. (From Mott *et al.*, 1986.)

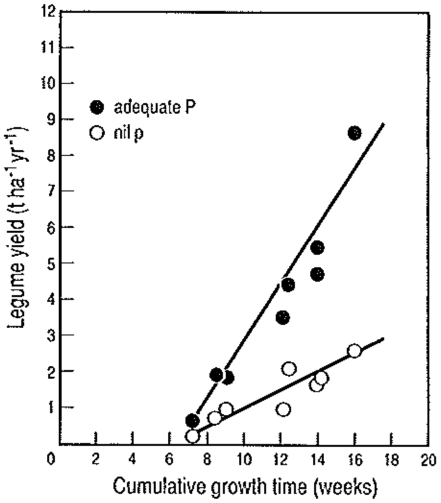

FIG. 11. The effect of P supply on the yield versus growth weeks relation for *Stylosanthes hamata* cv. Verano growth at 'Redlands' near Charters Towers on a red earth soil. (From Williams & Probert, 1983.)

Katherine and Pentland sites. At these sites the actual production of the native grasses falls well below potential production and shows small variation between the high and low rainfall years. When deficiencies of N and P were eliminated at Katherine, actual production increased to approximate the estimated potential production for the season. On the somewhat more fertile texture contrast soils at Woodstock, actual grass production approximated potential production implying that in these seasons grass yield was not nutrient constrained.

In a case where the vegetation was a sown legume (Williams & Probert, 1983) supply of adequate P to a severely P-deficient soil resulted in 3-4-fold increases in Caribbean stylo yield (Fig. 11). Yield is proportional to growth time (water supply) at both low and high P levels with difference in yield between the driest and wettest years exceeding 10-fold. However, the addition of P results in additional yield of only 1 t/ha in a season of 8 Growth Weeks, the same input results in an additional 6 t/ha in a season with 16 Growth Weeks.

In a grazing industry in which it is difficult to rapidly acquire or dispose of stock in response to feed supply, there is a problem of capitalizing on greatly improving production in good seasons except by increasing the normal stocking density. This, however, increases the risk of overstocking in dry years. In the nutrient-limited system, overgrazing in dry years is less of a problem because nutrient deficiencies keep normal stocking density low.

The effectiveness of rainfall is influenced by surface processes that affect the proportion of rain that enters the soil, i.e. rainfall interception, surface detention, overland flow, and infiltration. Much of the research specific to northern Australia has been conducted recently at study sites in little-disturbed savanna near Torrens Creek in central north Queensland. Water balance work by Williams & Coventry (1979, 1981) established that the water losses were by evapotranspiration and deep drainage alone with the implication that runoff was very small. Rainfall was shown to infiltrate and penetrate to depths in excess of 6 m in the deep massive sesquioxidic profiles. The eucalypt woodland extracted the water from similar depths during the dry season to yield a profile water store of approximately 480 mm.

In an undegraded state, the field saturated hydraulic conductivity is moderately high (50–80 mm h^{-1}) (Bonell & Williams, 1986; Williams & Bonell, 1988). These authors showed that under the high intensity rainfall of 60–120 mm/h^{-1} for storm durations of 20–30 min that, although Hortonion overland flow was rapidly generated, less than 2% was redistributed and this subsequently infiltrated. During high intensity rainfall the ponding depth increases, exposing higher points of the surface around tussocks to ponding. Bonell & Williams (1986) found that the conductivity of the higher surfaces near vegetation was often much greater than on the lower bare surfaces. The consequence of this was that the deeper surface ponding in the woodland the higher the effective hydraulic conductivity of the land surface. The tendency of runon to equal runoff is shown in Fig. 12. Here we see the net change in overland flow at locations down the hillslope being quite small and essentially cancelling each other out.

Water entry is sensitive to disturbance at the soil surface in these savanna woodlands. Overgrazing alters the hydrology by first reducing infiltration by reducing the surface roughness and the hydraulic resistance of tussock vegetation. Death of vegetation can lead to the formation of 'scalds' whose permeability is very low (Mott, Bridge & Arndt, 1979). With similar soil, slopes and rainfall intensities as studied by Williams & Bonell (1988) but for heavily utilized sown pasture on land previously cropped, Ive *et al.* (1976) found upwards of 37% of rainfall became overland flow which was lost as runoff. Preliminary results from the Croplands Erosion Research Project at Douglas Daly Experimental Farm also show the close relation of runoff and soil erosion to degree of disturbance in this savanna zone (Mohammed Dilshad, pers. comm.).

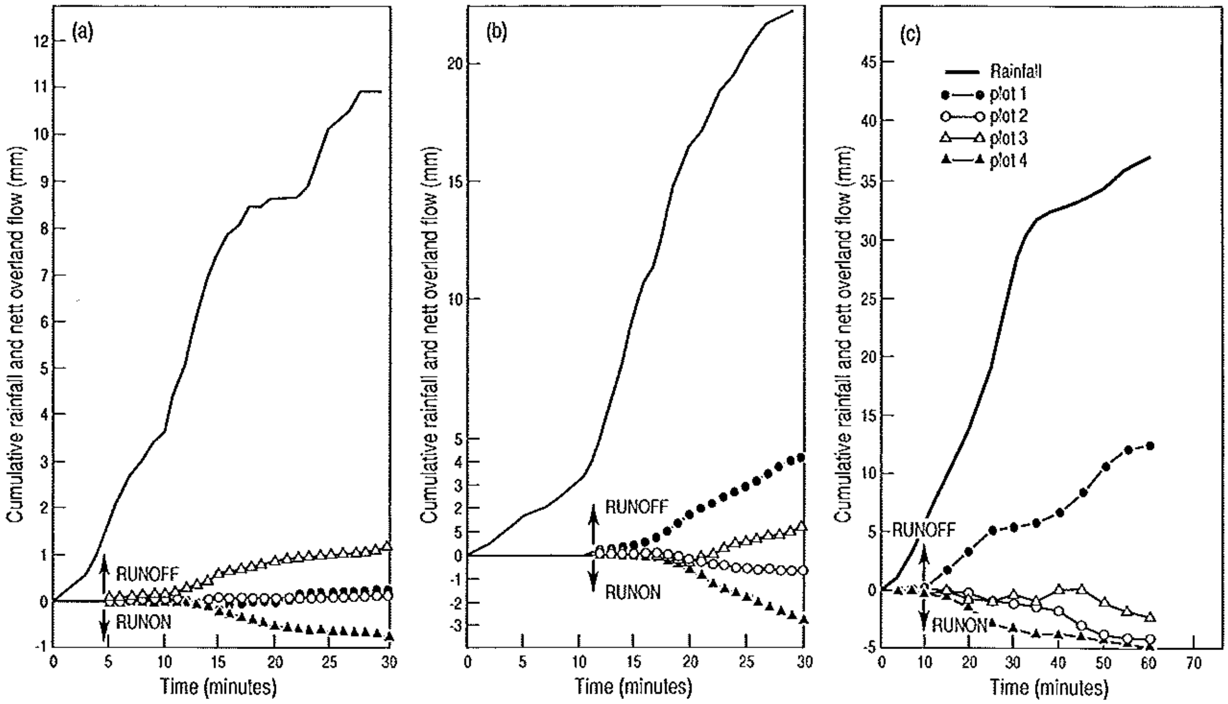

FIG. 12. Cumulative rainfall and net overland flow as a function of time for three storms (a) 10.8 mm, (b) 22.3 mm, and (c) 38.0 mm in Eucalypt Woodland on red earth soil near Torrens Creek. (From Williams & Bonell, 1988.)

CONCLUSION

Water deficits that severely limit plant growth are normal in the savanna zone, and an extensive beef industry which is adapted to this environment has existed in northern Australia for over 100 years. In recent years a revolution has been taking place that greatly reduces the inherent dependency of animal production on soil water supply via green grass. The first step has been the infusion of *Bos indicus* germplasm, resulting in cattle with greater tolerance of environmental stresses including the poor nutritional regime. The second step has been the widespread adoption of feeding non-protein nitrogen supplements in the dry season, which results in a further increase in herd productivity and a more complete utilization of dry grass herbage. Although not widely adopted, the sowing of legumes can greatly increase carrying capacity and individual production performance.

The recent succession of years with below-average rainfall has shown up the increased vulnerability of the savanna lands to overgrazing and soil erosion as a result of these technologies which enable more complete utilization of herbage. Although with a continuing cost-price squeeze, such intensification is necessary for continued economic viability, urgent changes in management that prevent ecologically damaging increases in herd size, e.g. greater turnoff of cows, are required. Much remains to be learned about management of the more intensively utilized pastoral ecosystem, but there seems to be little prospect for a return to the traditional low input/low productivity enterprise in spite of the appeal of its comparative ecological stability.

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