

# THE CLIMATIC POTENTIAL FOR BEEF CATTLE PRODUCTION IN TROPICAL AUSTRALIA: PART I—SIMULATING THE ANNUAL CYCLE OF LIVELWEIGHT CHANGE

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## SUMMARY

*This is the first of a series of papers dealing with a survey of the agricultural climate as it pertains to the beef cattle industry in northern Australia. Beef cattle production here, as in most of the tropics, is characterised by an annual periodicity of weight gain and loss in train with seasonal water supply and temperatures. Trends in a weekly growth index derived from a simulated water budget and mean daily temperatures were found to correlate with trends in liveweight changes. Criteria for estimating the start and cessation of a 'green season' and a 'dry season', corresponding to the main liveweight gain and loss periods respectively, are derived and validated using cattle liveweight data from seven locations and both native and improved pastures. Linkage between cattle liveweight change and climate was close on native grass pastures but not on legume-improved pastures.*

## INTRODUCTION

Over most of northern Australia the land is used for extensive cattle grazing. The predominant pasture vegetation is tropical grass dominated by the genera *Themeda*, *Heteropogon* or *Sorghum*, occurring mainly in open *Eucalyptus* woodland communities (Moore, 1970). The livestock industry of the region produces about a quarter of the beef cattle in Australia, mainly for export as chilled manufacturing beef (Shaw & Norman, 1970). Although median annual rainfall in the region is relatively high

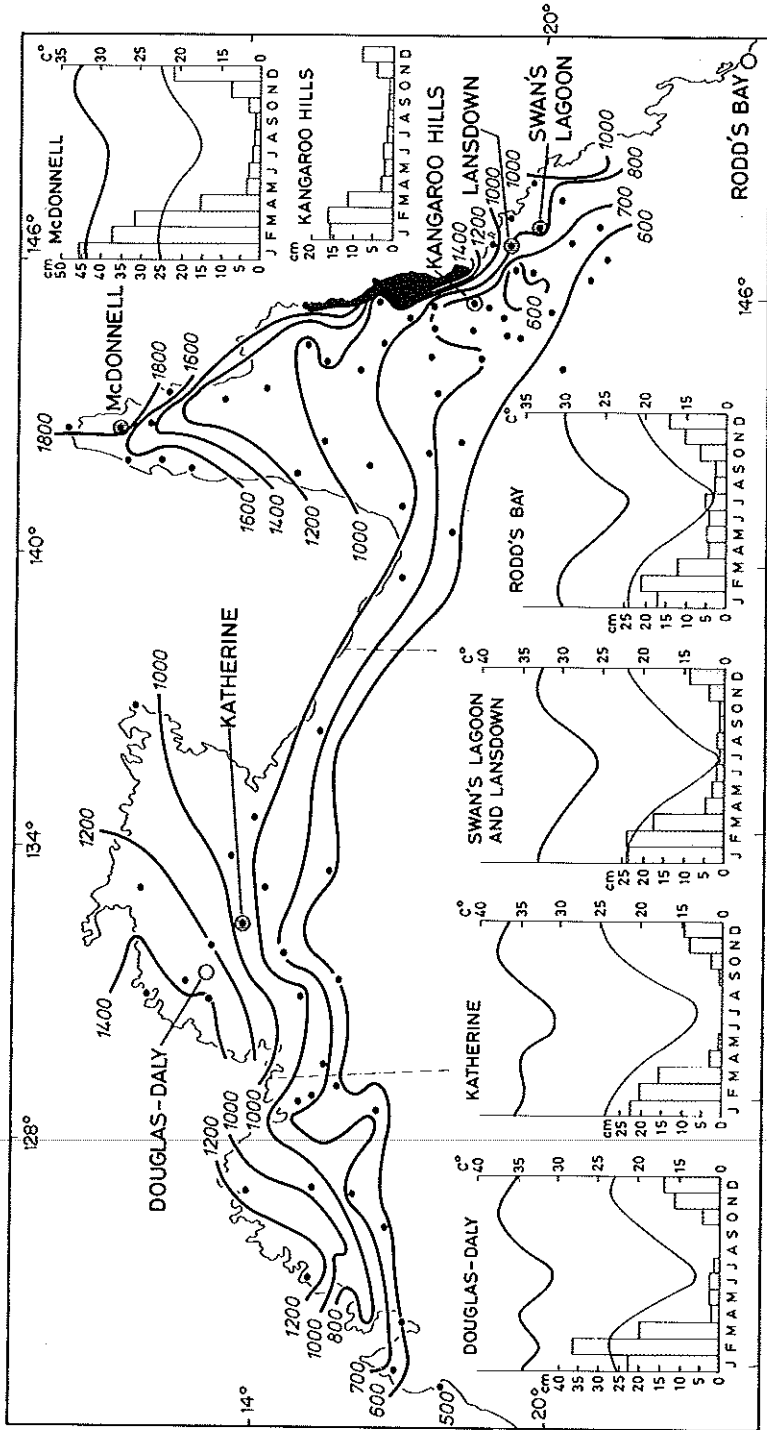


Fig. 1. Isopleths of median green season rainfall; location of cattle production experiments described in the Appendix A (⊙); mean monthly rainfall and mean daily maximum and minimum temperatures for these stations; and location of meteorological stations used in the survey (●) (see text). Shaded area represents the wet coast and tablelands not included in the study.

(Fig. 1), animal production is severely constrained by a season of little or no rain; mean seasonal patterns for six areas have been superimposed on Fig. 1. Cattle gain weight during the period when conditions are favourable for pasture growth, but they lose weight during the 4 to 7 month season when conditions are too dry and/or too cold for pasture growth. Reproductive rates of cows range from 30 to 75% and the time to turn off a bullock for slaughter is 4 to 6 years (Donaldson *et al.*, 1967; Yeates & Schmidt, 1974). Profitability in much of the region has been possible only by the minimising of capital inputs and with the assistance of preferential government policies.

While providing various forms of short-term financial relief, the long-term policy of both state and national governments has been to promote the development of the northern beef industry. A basic contribution has been the development of methods for survey of the production resources of large areas of land and implementation of surveys in several northern areas (Christian & Stewart, 1968). An important aspect of the development of survey methodology has been the evaluation of means for assessing the climatic constraints to production. In this seasonally-dry tropical region, this has featured a description of the water regime using a water balance modelling approach based on that of Slatyer (1960). Initially, weekly pasture growth activity was estimated by using arbitrary levels of simulated soil water storage and was used to define a seasonal period of 'active' growth and a longer period of 'useful' growth. Maps and probability tables for the date of initiation and for the duration of these periods of assumed importance to animal production were published for several areas of northern Australia (Fitzpatrick & Arnold, 1964; Fitzpatrick, 1965; McAlpine, 1969, 1976). A later methodological development (Fitzpatrick & Nix, 1970) was the use of a simple index to express the relative favourability of each important climatic factor, e.g. moisture, temperature, light; an index value is the dry matter production rate at a given factor level relative to the rate at an optimal level of that factor. The combined effects of all factors for each week is expressed as a 'growth index', calculated as the product of the individual indices for that week. Since the water balance model provides the moisture index, this is a natural extension of the earlier method but provides a considerably more powerful derived variable, i.e. the 'growth index'.

As discussed by Isbell & McCown (1976), simulation methods using standard meteorological data promise increasingly quantitative applications in pastoral land evaluation. There is ample evidence that the approach is effective in predicting soil water changes (McCown, 1973; Johns & Smith, 1975) and in accounting for variation in dry-matter production for a given pasture type (McCown, 1973; McCown *et al.*, 1974; Peake *et al.*, 1979). The methods have been extended to predict sheep and wool production (Reid & Thomas, 1973; Rich & Taylor, 1977) but not, to the author's knowledge, to beef production. Furthermore, although these methods were developed for use in evaluating pastoral lands in northern Australia,

implementation has been mainly as part of 'integrated surveys' which included surveys of geomorphology, soil and vegetation as well as climate (Christian & Stewart, 1968); to date such surveys have been conducted for only a fraction of tropical Australia. The work reported here was undertaken to remedy these two major deficiencies and, hence, had a twofold aim: to test the approach using beef cattle production data obtained from sites and pastures over a wide environmental range; and to describe the geographic and year-to-year variability in those aspects of climate with important effects on cattle production for all of tropical Australia, with the exception of the small area of wet coast and tablelands of Queensland shaded in Fig. 1.

#### DATA AND METHODOLOGY

##### *Animal production data*

Cattle liveweight data were taken from 15 studies at seven locations; relevant details are given in Appendix A. Rodd's Bay, although subtropical, was included because of the abundance of liveweight data available; moreover, it was expected to provide a more rigorous test of a temperature model than would otherwise have been possible. Weighings were weekly in data set No. 10 and monthly or four-weekly in the remainder. Pan evaporation measurements for the duration of the experiments existed for Lansdown, Katherine and McDonnell.

##### *The model: moisture index*

The basic water-balance model was similar to that used by McAlpine (1970). The input consisted of actual weekly rainfall and average weekly Australian tank or 0.85 Class A pan. Where evaporation data were not available, weekly values were taken from maps of monthly estimated Australian tank evaporation (Anon., 1968). Fifty-two standard weeks were defined, as shown in Appendix B (Keig & McAlpine, 1969). The model assumes (i) that plant-available water in the soil is equally distributed throughout a single store, (ii) that infiltration rate is unrestricted until the soil store is full, subsequent rainfall being considered as 'rainfall excess' (drainage + surface runoff), (iii) that the ratio of actual evapotranspiration (ET) to potential ET = 1 when the soil store is more than half full, (iv) that this ratio, the moisture index (MI) of Fitzpatrick & Nix, (1970); R-index of Yao, (1969), declines linearly from 1 to 0 as the soil store dries from half full to empty, and (v) that the ratio of the maximum ET to input evaporation (the 'crop factor') is constant throughout the year. The first system parameter, the soil storage capacity, was set at 150 mm for all sites, based on results of previous studies at Lansdown (McCown, 1973) and at Katherine (McCown & Wall, unpublished data). Substituting alternative values for the other stations did not improve predictions. The second system parameter, the crop factor,

was initially set at 0.80 (McAlpine, 1970) and then reduced to 0.75 to achieve a somewhat better prediction.

*Temperature index*

Although pastures in the Australian tropics are predominantly grass, the growing of legumes in association with the grass is a practice of great potential importance. The present study did not attempt to distinguish between separate grass and legume components, but it was considered important that the simulated environment output should apply to both native grass and legume-improved pastures. Relationships specific for any native grasses were obviated by the lack of physiological research on this group. At the time, the most pertinent data available were those of Fitzpatrick & Nix (1970) and Sweeney & Hopkinson (1975). The relationship selected was a simplified version of the generalised tropical legume curve of Fitzpatrick & Nix (1970) (Fig. 2). Since this function lay approximately midway between the very contrasting tropical grass functions of the two groups of workers, it was both the legume function and the best available 'average' grass function. More recent work by Ivory (1978) suggests that the slope of the selected function was somewhat steep for grasses (Fig. 2).

The growth index (GI) was defined as the product of the moisture and temperature indices and is necessarily constrained between 0 and 1.

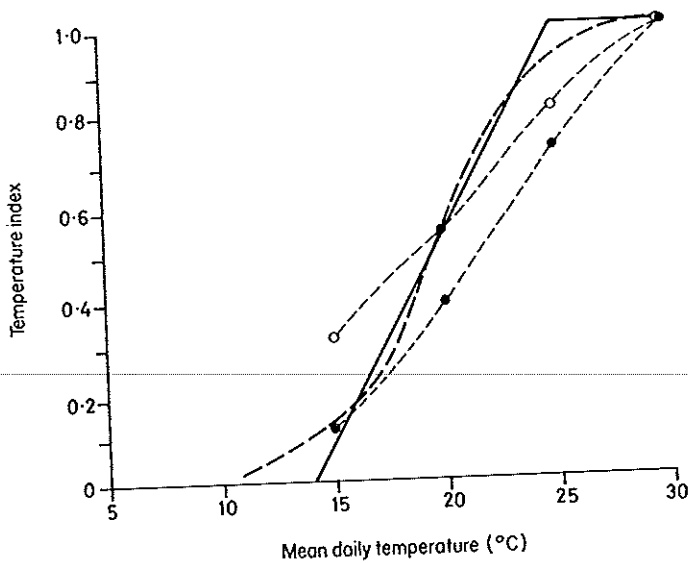


Fig. 2. Thermal response curves for tropical grasses and legumes. Dashed line, generalised tropical legume curve from Fitzpatrick & Nix (1970); O green panic, ● buffle grass from Ivory (1978); solid line, model used in deriving temperature index in present study.

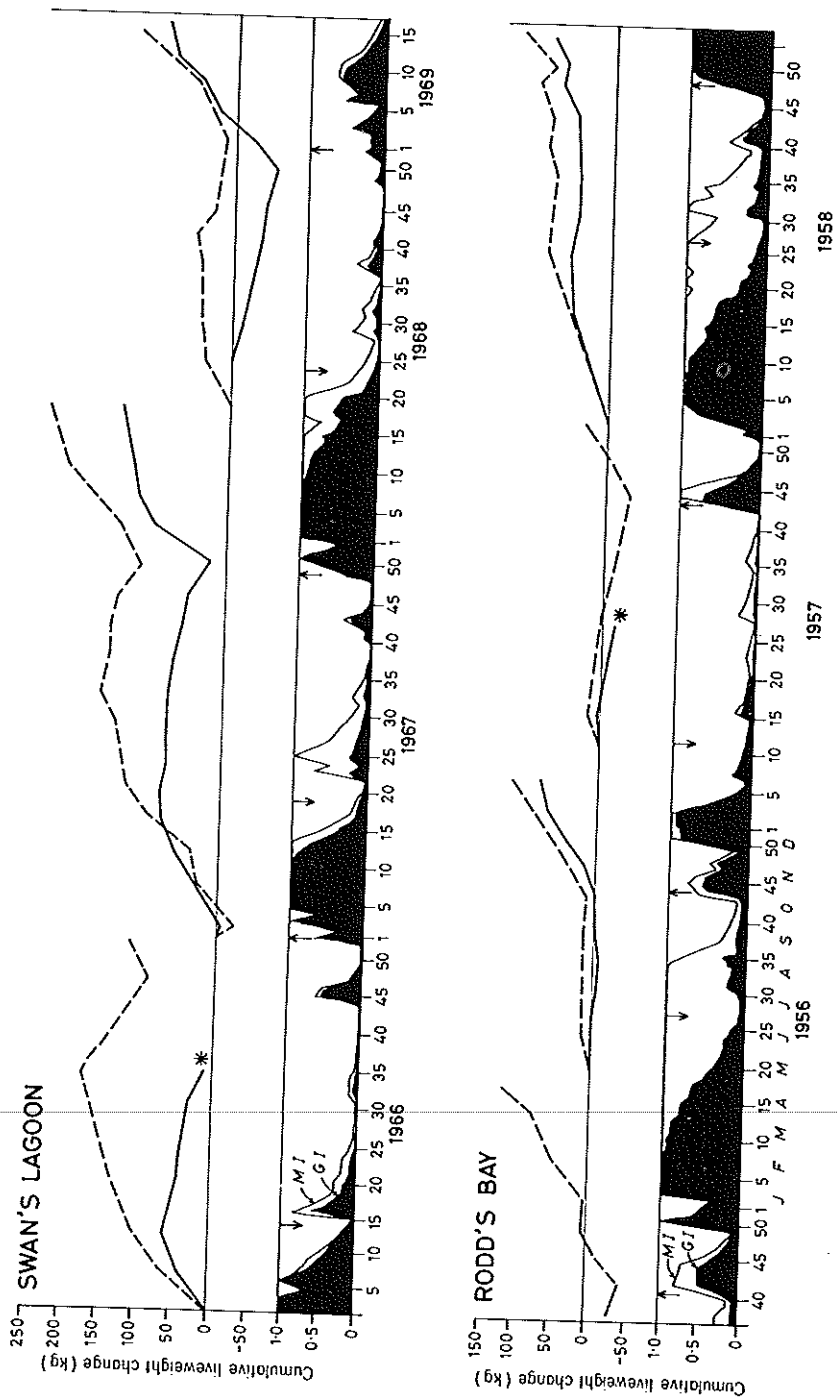


Fig. 3. Actual cattle liveweight changes in relation to seasonal changes in the moisture index and growth index (shaded). (Solid line, native pasture; broken line, native pasture and Townsville stylo. ↑ indicates initiation of green season (GOWK); ↓ indicates cessation of green season (STOPWK); \* indicates removal of cattle to prevent death; re-initiation of cumulative liveweight gain to zero indicates cattle replacement.)

## RESULTS

*Weekly predictions of liveweight trends*

It will suffice for the present purpose to present results from two contrasted sites. Figure 3 shows weekly changes in moisture index, growth index and cumulative liveweight gain for native and improved pastures at Swan's Lagoon and Rodd's Bay. Two effects are immediately apparent. First, at the tropical site of Swan's Lagoon the effect of low temperature on the GI was relatively slight, and the moisture index accounts for most of the variation in liveweight. However, at the subtropical site the moisture index alone is quite inadequate; there were evidently a number of weeks during which the soil store was virtually full but the temperature too low for rapid growth. Secondly, it is clear, especially at Swan's Lagoon, that the prediction for improved pasture is markedly inferior to that for native pasture.

Others have found that whereas cattle on native grass pasture may gain weight at a rate as great as those on pasture containing legume early in the growing season, the benefit of the legume increases as the season progresses (Gillard, 1979; Hunter *et al.*, 1976). This appears to be related to the decline of nitrogen in the all-grass diet in spite of favourable growing conditions (Hunter *et al.*, 1976). Moreover, with the onset of the dry season, the decline in the quality of Townsville stylo tissue is much less drastic than that of grasses (Norman, 1967; Playne, 1972); valuable nutrients can thus be stored in the mature or dry legume content of the pasture. The dependence of liveweight gain on the growth index is thereby lessened, and one way of viewing the contribution of the legumes is that they reduce the degree of coupling of animal nutrition to climate.

*Seasonal considerations*

*Definitions and requirements:* The most fundamental characteristic of the northern Australian environment, and, indeed, most of the world's tropics, is the annual wet-dry cycle. This cycle, therefore, provides a natural basis for the further development of relationships between climate and animal production. It is then necessary to define the two seasons using a climatically-derived pasture growth variable, and to explore the relationship between cattle growth and season. The 'dry' season is generally characterised by dryness, so the term seems most appropriate, even though at some times in some places substantial rain occurs and low temperatures may prevail. However, the common terms 'wet season' or 'rainy season' ignore the fact that when the rain has ceased there is a period when there is a substantial amount of stored water. During this period cattle are able to select sufficient green foliage from native grass pastures to gain weight. In this paper the term 'green season' will be used to cover the true 'wet' or 'rainy' season plus its stored water extension. We then need to define the beginning and end of the green season by reference to changes in the growth index.

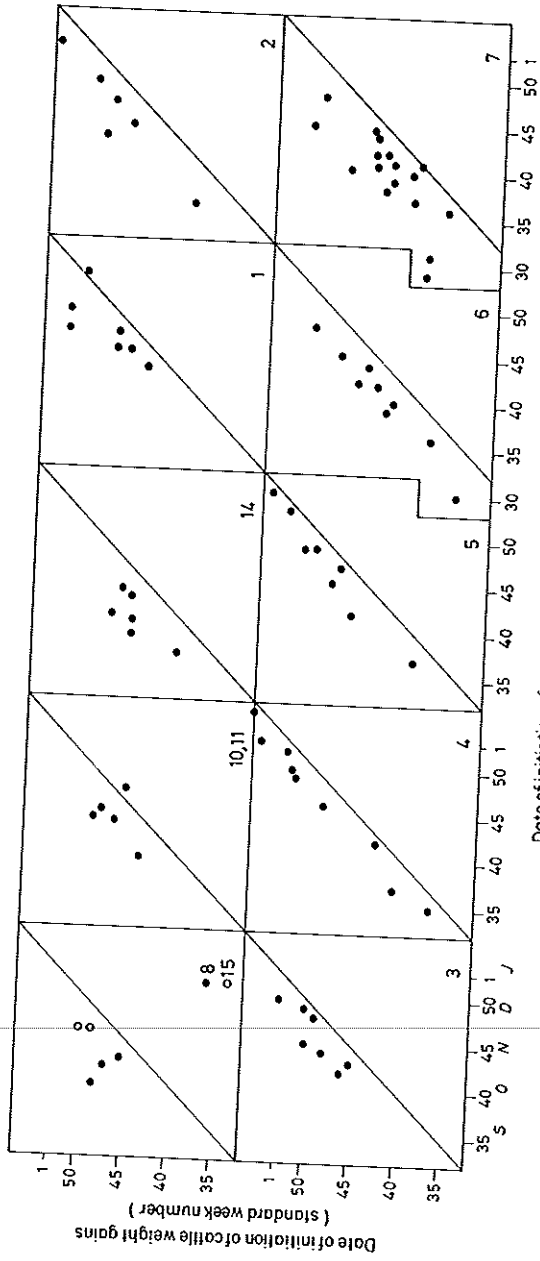


Fig. 4. Scatter diagrams of the data of first cattle weight increase (mid-point of weighing interval) and the date of initiation of the green season (GOWK). Identification numbers refer to data sets in the Appendix A.



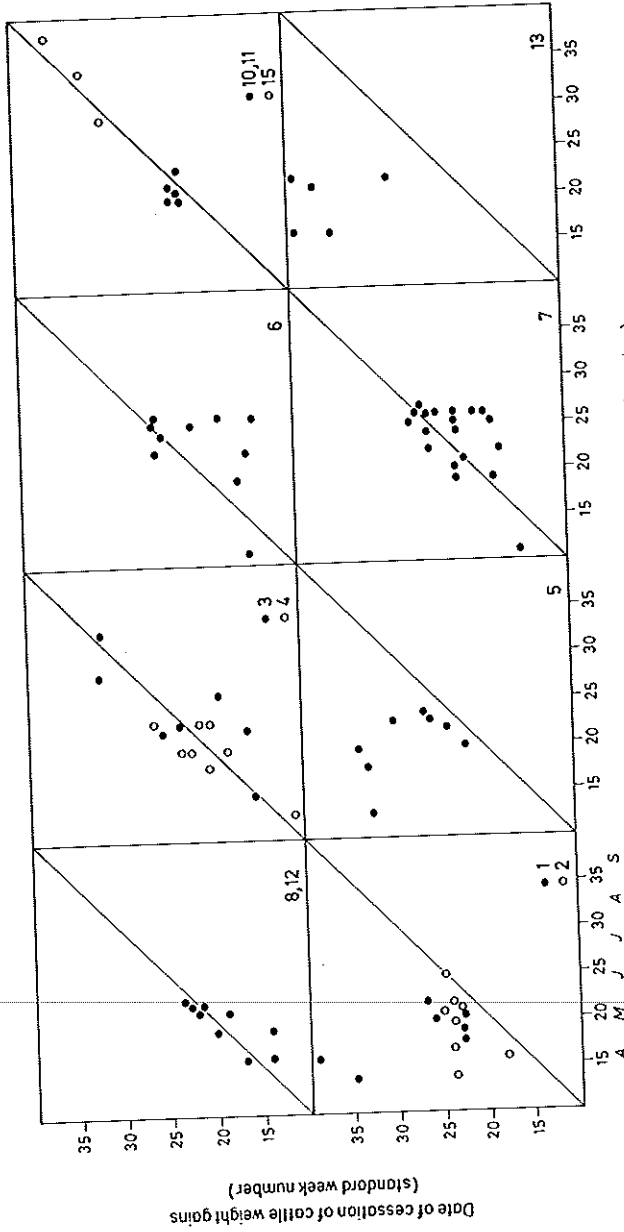


Fig. 5. Scatter diagrams of the date of cessation of cattle weight gain (date of maximum cumulative weight) and the date of cessation of the green season (STOPWK). Identification numbers refer to data sets in the Appendix A.

*Date of commencement of the green season (GOWK):* The weather at the start of the green season is characterised by local falls of rain and high evaporation rates. Although such rainfall events may provide soil water to initiate pasture growth, cattle weight gains may be only transient for want of 'follow up' rains. The criterion for the start of a green season in this study was, therefore, the occurrence of GI values which initiated the main period of liveweight gain. Of the several combinations of GI values and sequences examined, the date of the beginning of a sequence in which GI values exceeded 0.1 in both (a) three of the first four weeks and (b) six of the first eight weeks correlated best with the start of sustained cattle weight gains. Thus in Fig. 3, at Swan's Lagoon in 1967, weeks 40-45, 36 mm of rain produced a pulse in the GI insufficient to satisfy this green season initiation criterion; nor did cattle show any positive response. In 1966, weeks 45-50, 68 mm rain produced a pulse (GI exceeding 0.1 for four consecutive weeks, but not for six of the first eight) which resulted in weight gain but subsequent loss; admittedly, this may be an artefact due to replacement of cattle. At Rodd's Bay, pulses produced by storms in weeks 40-45 of each year were sufficient to satisfy the GOWK criteria, and in all cases correspond well with the start of the main cattle growth periods.

Figure 4 shows the relation between GOWK and the week of the start of the main cattle gain period (mid-point of first weight-gain interval) for 12 of the data sets. In general, GOWK occurred two to five weeks prior to weight gains. Some of the discrepancies observed may be due to non-climatic constraints on cattle gains. For example, in each of data sets 1 and 2 there is an extreme outlier where the weight-gain commencement appears to be abnormally late; but cattle in adjacent paddocks (not shown in graph) began gaining weight four weeks earlier in these seasons.

*Date of cessation of the green season (STOPWK):* Whereas the green season normally begins abruptly, it ends gradually as soil dries and/or temperatures fall. In the case of native pastures at Swan's Lagoon in 1966 (Fig. 3), cattle ceased gaining weight at about week 12 when both MI and GI fell to low values; in 1967 this occurred at about week 20, and at Rodd's Bay in 1957 about week 15. In the other years depicted in Fig. 3, cessation of liveweight gain on native pasture corresponded with the decline of the GI to low values with an important or dominant low-temperature effect. The criterion (STOPWK) for terminating the green season was two consecutive weeks with GI less than 0.1, STOPWK itself being defined as the week number of the first of these two weeks.

Figure 5 shows, for 13 of the data sets, the relation between STOPWK and the date of cessation of liveweight gain. In the native-pasture data sets 3, 4, 8 and 12, and the sown-grass dominant sets 10, 11 and 15, there is good accord between the two measures. On the Townsville stylo pasture in the very dry winter environment of Katherine (data set 13), cattle gains were independent of STOPWK and continued until the Townsville stylo was consumed or until rain destroyed its quality (Woods, 1970). Data from experiments with a variable Townsville stylo component (data sets

1, 2 and 5) show variable underestimation by STOPWK. This again is a demonstration of the 'uncoupling' effect between climate and animal production produced by the presence of legumes.

#### DISCUSSION

The compartmentalisation of herbage into green and dry greatly simplifies simulation of animal performance in wet-dry environments. Willoughby (1959) and 't Mannetje (1974) found liveweight gain to be closely related to quantity of green forage. More complex models of animal production on pastures have utilised the green-dry concept in predicting herbage intake and nutritive values (Freer *et al.*, 1970; Vickory & Hedges, 1972; Arnold & Campbell, 1972). The approach taken in the present study is conceptually similar but greatly simplified. Instead of relating liveweight change to amount of green forage, it is related to the cumulative time that green feed availability is above or below a critical (but undefined) threshold as predicted by the GI.

Obvious advantages of this approach are the lower information requirement for formulation and testing of models and the requirement of only input that is generally available, i.e. standard meteorological data; a drawback is the limitation of their use to simple systems. The GOWK criterion, based on the pattern of GI changes, proved a consistent predictor of the start of the liveweight gain period over a very wide range of climates and pasture types. However, although the model is evidently adequate to predict the cessation of gain in all-grass pastures, it is inadequate for pastures containing substantial proportions of legume. The quality of grass forage appears closely related to current GI; models for pastures improved with legumes will need to include provision for dealing with quantity and quality of components that are not always dependent on current growing conditions.

In this exercise the model has been used only qualitatively to predict only the beginning and cessation, but not the amount, of liveweight gain or loss. It is clearly desirable to ascertain to what extent this approach can be used in this quantitative way; this will be the subject of the second paper in this series.

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APPENDIX A  
 BACKGROUND INFORMATION OF THE EXPERIMENTS WHICH SUPPLIED THE CATTLE LIVEWEIGHT DATA FOR THIS STUDY

Data set	Location	Years	Pasture vegetation	Environment modification	Stocking density (beasts/ha)	Cattle breed	Source of data
1	Lansdown Res. Station	65-72	Native pasture, Townsville stylo	Trees cleared	Ave. 0.41, 0.82	Brahman x weaners	L. Edey, CSIRO, Townsville, (personal communication)
2	Lansdown Res. Station	67-74	Native pasture, Townsville stylo	Superphosphate	0.56	Brahman x steers	P. Gillard, CSIRO, Townsville, (personal communication)
3	Kangaroo Hills	65-72	Native pasture	Nil	0.21	Shorthorn and Brahman x steers	P. Gillard, CSIRO, Townsville, (personal communication)
4	Swan's Lagoon Fid. Stn.	65-74	Native pasture	Nil	0.25	Shorthorn and Brahman x steers	Winks, <i>et al.</i> (1974)
5	Swan's Lagoon Fid. Stn.	65-74	Townsville stylo, annual grasses	High superphosphate	0.50	Shorthorn and Brahman x steers	L. Winks, Q'land Dept. Primary Industries, Brisbane (personal communication)
6	Rodd's Bay	56-66	Native pasture	Trees killed	0.28	Brahman x steers	Shaw (1961)
7	Rodd's Bay	55-73	Townsville stylo, native grasses	Trees cleared High superphosphate	0.60	Hereford steers Hereford steers	Shaw and Manneje (1970)
8	Katherine Res. Station	55-58	Native pasture	Phosphate supplement fed	0.14	Shorthorn steers	N. Shaw, CSIRO, Brisbane (personal communication)
9	Katherine Res. Station	69-74	Native pasture	Nil	0.25	Shorthorn steers	Norman & Arndt (1959)
10	Katherine Res. Station	69-72	<i>Urochloa mosambicensis</i> , Townsville stylo	Trees cleared	2.5	Shorthorn steers	Norman (1963)
11	Katherine Res. Station	75-78	<i>Urochloa mosambicensis</i> , Townsville stylo	Medium superphosphate Trees cleared	1.7	Brahman x steers	Ive (1976)
12	Katherine Expt. Farm	63-66	Native pasture	High superphosphate Nil	0.10	Belmont red steers Shorthorn steers	W. Winter, CSIRO, Katherine (personal communication)
13	Katherine Expt. Farm	63-66	Townsville stylo	Trees cleared	1.7	Shorthorn steers	Woods (1970)
14	Douglas Daly Expt. Farm	67-74	<i>Urochloa mosambicensis</i> , Townsville stylo	High superphosphate Trees cleared	1.25	Shorthorn steers	Woods (1970)
15	McDonnell	73-75	<i>Brachiaria decumbens</i> , <i>Stylosanthes guyanensis</i> cv. Endeavour.	High superphosphate Trees cleared	1.9	Shorthorn steers Brahman x steers	J. Austin, Dept. of Northern Territory, Darwin (personal communication) Winter <i>et al.</i> (1977)

## APPENDIX B

Week no.	Date	Week no.	Date
1	Jan. 1–Jan. 7	27	Jul. 2–Jul. 8
2	Jan. 8–Jan. 14	28	Jul. 9–Jul. 15
3	Jan. 15–Jan. 21	29	Jul. 16–Jul. 22
4	Jan. 22–Jan. 28	30 <sup>b</sup>	Jul. 23–Jul. 30
5	Jan. 29–Feb. 4		
6	Feb. 5–Feb. 11	31	Jul. 31–Aug. 6
7	Feb. 12–Feb. 18	32	Aug. 7–Aug. 13
8	Feb. 19–Feb. 25	33	Aug. 14–Aug. 20
9 <sup>a</sup>	Feb. 26–Mar. 4	34	Aug. 21–Aug. 27
		35	Aug. 28–Sept. 3
10	Mar. 5–Mar. 11	36	Sept. 4–Sept. 10
11	Mar. 12–Mar. 18	37	Sept. 11–Sept. 17
12	Mar. 19–Mar. 25	38	Sept. 18–Sept. 24
13	Mar. 26–Apr. 1	39	Sept. 25–Oct. 1
14	Apr. 2–Apr. 8	40	Oct. 2–Oct. 8
15	Apr. 9–Apr. 15	41	Oct. 9–Oct. 15
16	Apr. 16–Apr. 22	42	Oct. 16–Oct. 22
17	Apr. 23–Apr. 29	43	Oct. 23–Oct. 29
		44	Oct. 30–Nov. 5
18	Apr. 30–May 6	45	Nov. 6–Nov. 12
19	May 7–May 13	46	Nov. 13–Nov. 19
20	May 14–May 20	47	Nov. 20–Nov. 26
21	May 21–May 27	48	Nov. 27–Dec. 3
22	May 28–Jun. 3		
23	Jun. 4–Jun. 10	49	Dec. 4–Dec. 10
24	Jun. 11–Jun. 17	50	Dec. 11–Dec. 17
25	Jun. 18–Jun. 24	51	Dec. 18–Dec. 24
26	Jun. 25–Jul. 1	52	Dec. 25–Dec. 31

<sup>a</sup> Week 9 has 8 days in each leap year.

<sup>b</sup> Week 30 has 8 days in every year (see text).

## REFERENCES

- ANON. (1968). *Review of Australia's water resources, monthly rainfall and evaporation, part 2*, Bureau of Meteorology for the Australian Water Resources Council, Melbourne, 52 pp.
- ARNOLD, G. W. & CAMPBELL, N. A. (1972). A model of a ley farming system, with particular reference to a sub-model for animal production, *Proc. Aust. Soc. Anim. Prod.*, **9**, 23–30.
- CHRISTIAN, C. S. & STEWART, G. A. (1968). Methodology of integrated surveys, in: *Aerial Surveys and Integrated Studies*, Proc. Toulouse Conf., 1964 Paris, UNESCO, pp. 233–80.
- DONALDSON, L. E., RITSON, J. B. & COPEMAN, D. B. (1967). The reproductive efficiency of several north Queensland beef herds, *Aust. Vet. J.*, **43**, 1–6.
- FITZPATRICK, E. A. (1965). Climate of the Tipperary area, *CSIRO Aust. Land Res. Ser.*, No. 13, 39–52.
- FITZPATRICK, E. A. & ARNOLD, J. M. (1964). Climate of the West Kimberley area, *CSIRO Land Res. Ser.*, No. 9, 76–102.
- FITZPATRICK, E. A. & NIX, H. A. (1970). The climatic factor in Australian grassland ecology, in: Moore, R. M. (ed.), *Australian Grasslands*, Aust. National Univ. Press, Canberra, pp. 3–26.
- FREER, M., DAVIDSON, J. L., ARMSTRONG, J. S. & DONNELLY, J. R. (1970). Simulation of summer grazing, *Proc. 11th Int. Grassland Congress, Surfers Paradise, Qld.*, pp. 913–24.
- GILLARD, P. (1979). Improvement of native pasture with Townsville stylo in the dry tropics of sub-coastal northern Queensland, *Aust. J. Agric. Anim. Husb.*, **19**, 325–36.

- HUNTER, R. A., SIEBERT, B. D. & BREEN, M. J. (1976). The botanical and chemical composition of the diet selected by steers grazing Townsville stylo pastures during a period of liveweight gain, *Proc. Aust. Soc. Anim. Prod.*, 11, 457-60.
- ISBELL, R. F. & McCOWN, R. L. (1976). Land, in: Shaw, N. H. & Bryan, W. W. (eds.), *Tropical Pasture Research, Bulletin 51*, Comm. Bur. Pastures and Crops, Hurley, pp. 34-50.
- IVE, J. R. (1976). Simulating change in cattle liveweight during the transition period in a dry monsoonal climate, *Aust. J. Agric. Res.*, 27, 297-307.
- IVORY, D. (1978). Effect of temperature on growth of five subtropical grasses. 1. Effect of day and night temperature on growth and morphological development, *Aust. J. Plant Physiol.*, 5, 149-57.
- JOHNS, G. G. & SMITH, R. C. G. (1975). Accuracy of soil water budgets based on a range of relationships for influence of soil water availability on actual water use, *Aust. J. Agric. Res.*, 26, 871-83.
- KEIG, G. & McALPINE, J. R. (1969). Instructions for preparation of daily rainfall data as input to Land Research climate programme, *CSIRO Land Res. Tech. Mem.*, 69/8.
- McALPINE, J. R. (1969). Climate of the Adelaide-Alligator area, *CSIRO Land Res. Ser.*, No. 25, 49-55.
- McALPINE, J. R. (1974). Estimating pasture growth periods and droughts from simple water balance models, *Proc. 11th Int. Grassland Congr., Surfers Paradise, Qld.*, pp. 484-7.
- McALPINE, J. R. (1976). Climate and water balance of the Alligator Rivers area, Northern Territory, *CSIRO Land Res. Ser.*, No. 38, 35-49.
- McCOWN, R. L. (1973). An evaluation of the influence of available soil water storage capacity on growing season length and yield of tropical pastures using simple water balance models, *Agric. Meteor.*, 11, 53-63.
- McCOWN, R. L., GILLARD, P. & EDYE, L. A. (1974). The annual variation in yield of pastures in the seasonally-dry tropics of Queensland, *Aust. J. Exp. Agric. Anim. Husb.*, 14, 328-33.
- MANNETJE, L. 'T (1974). Relations between pasture attributes and liveweight gains on a sub-tropical pasture, *Proc. 12th Int. Grassland Congress, Moscow*, pp. 200-304.
- MOORE, R. M. (1970). Australian Grasslands, in: Moore, R. M. (ed.), *Australian Grasslands*, Aust. National Univ. Press, Canberra, pp. 87-100.
- NORMAN, M. J. T. (1963). Wet-season grazing of sown pastures and fodder crop at Katherine, Northern Territory, *CSIRO Aust. Div. Land Res. Reg. Surv. Tech. Pap.*, No. 22.
- NORMAN, M. J. T. (1967). Complementary grazing of native pasture and standing Townsville lucerne in the dry season at Katherine, Northern Territory, *Aust. J. Exp. Agric. Anim. Husb.*, 7, 225-8.
- NORMAN, M. J. T. & ARNDT, W. (1959). Performance of beef cattle on native and sown pasture at Katherine, Northern Territory, *CSIRO Aust. Div. Land Res. Reg. Surv. Tech. Pap.*, No. 4.
- PEAKE, D. C. I., HENZELL, E. F. & STIRK, G. B. (1979). Simulation of changes in herbage biomass and drought response of a buffel grass (*Cenchrus ciliaris* cv. Bilocla) in southern Queensland, *Agroecosystems*, 5, 23-40.
- PLAYNE, M. J. (1972). Nutritional value of Townsville stylo (*Stylosanthes humilis*) and of spear grass (*Heteropogon contortus*)—dominant pastures fed to sheep. 1. The effect of plant maturity, *Aust. J. Exp. Agric. Anim. Husb.*, 12, 365-72.
- REID, G. K. R. & THOMAS, D. A. (1973). Pastoral production, stocking rate and seasonal conditions, *Quart. Rev. Agric. Econ.*, 26, 217-27.
- RICH, M. M. & TAYLOR, N. W. (1977). Econometric models for forecasting the national tailing percentage and wool slip, *New Zealand Agric. Sci.*, 11, 65-72.
- SHAW, N. H. (1961). Increased beef production from Townsville lucerne (*Stylosanthes sundaica* Taub.) in the spear grass pastures of central coastal Queensland, *Aust. J. Exp. Agric. Anim. Husb.*, 1, 73-80.
- SHAW, N. H. & MANNETJE, L. 'T (1970). Studies on a spear grass pasture in central coastal Queensland—the effect of fertilizer, stocking rate, and oversowing with *Stylosanthes humilis* on beef production and botanical composition, *Trop. Grasslds.*, 4, 43-56.
- SHAW, N. H. & NORMAN, M. J. T. (1970). Tropical and sub-tropical woodlands and grasslands, in: Moore, R. M. (ed.), *Australian Grasslands*, Aust. National Univ. Press, Canberra, pp. 112-22.
- SLATYER, R. P. (1960). Agricultural climatology of the Katherine area, Northern Territory, *CSIRO Aust. Div. Land Res. Reg. Survey Tech. Pap.*, No. 13.
- SWEENEY, F. C. & HOPKINSON, J. M. (1975). Vegetative growth of nineteen tropical and sub-tropical pasture grasses and legumes in relation to temperature, *Trop. Grasslds.*, 9, 209-18.
- VICKORY, P. J. & HEDGES, D. A. (1972). A productivity model of improved pasture grazed by merino sheep, *Proc. Aust. Soc. Anim. Prod.*, 9, 16-22.
- WILLOUGHBY, W. M. (1959). Limitations to animal production improved by seasonal fluctuations in pasture and by management procedures, *Aust. J. Agric. Res.*, 26, 248-68.

- WINKS, L., LAMBERTH, F. C., MOIR, K. W. & PEPPER, P. M. (1974). Effect of stocking rate and fertilizer on the performance of steers grazing Townsville-stylo based pasture in north Queensland, *Aust. J. Exp. Agric. Anim. Husb.*, **14**, 146-54.
- WINTER, W. H., EDYE, L. A. & WILLIAMS, W. T. (1977). Effects of fertilizer and stocking rate on pasture and beef production from sown pastures in northern Cape York Peninsula. 2. Beef production and its relation to blood, faecal, and pasture measurements, *Aust. J. Exp. Agric. Anim. Husb.*, **17**, 187-96.
- WOODS, L. E. (1970). Beef production from pastures and forage crops in a tropical monsoon climate, *Proc. 11th Int. Grassland Congr.*, Surfers Paradise, Qld., pp. 845-9.
- YAO, A. Y. M. (1969). The R-index for plant water requirement, *Agric. Meteor.*, **6**, 259-73.
- YEATES, N. J. M. & SCHMIDT, P. J. (1974). *Beef Cattle Production*, Butterworths, London.
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