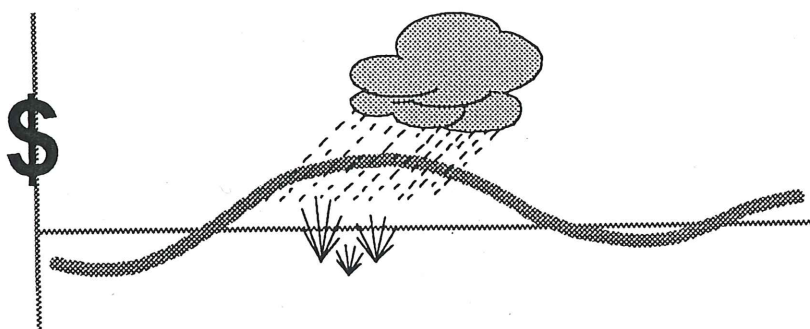


DroughtPlan

*Developing, with graziers, profitable and sustainable strategies to
manage for rainfall variability*



Modelling of research data on reproduction and mortality of cattle and sheep

A.D. Moore, D.G. Mayer, P.M. Pepper & M. Freer

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INTRODUCTION

The DroughtPlan project is seeking to develop profitable and sustainable strategies for managing climatic variability in the grazing lands of Australia. One of the key linkages between variability in rainfall and variability in economic production lies in differences between seasons in the "biological rates" of flocks and herds, i.e. the rates of animal mortality and reproduction (e.g. Foran *et al.* 1990). Our lack of understanding of this link is a significant bottleneck in our ability to analyse the effects of climatic variability on pastoral systems, especially in the rangelands.

This study uses previously collected data from grazing trials and monitoring studies to obtain an overview of spatial and temporal variation in these key biological rates. Potential predictors of mortality and reproduction, including equations from the GRAZPLAN process models, are discussed and screened. Further testing of these predictors against data from producers' paddocks will be the subject of a later report.

THE GRAZPLAN MORTALITY AND CONCEPTION SUBMODELS

The GRAZPLAN mortality and conception submodels are part of a larger model of ruminant biology designed for general use in southern Australian conditions (Freer *et al.*, submitted).

Before discussing the equations for mortality and conception rate, it is necessary to make some preliminary definitions. Standard reference weight, SRW , is defined in SCA (1990) as the live weight excluding fleece and conceptus, W , of an animal when skeletal development is complete and condition score is in the middle of the range. SRW must be provided by the user of these models.

The normal weight, N , of a mature animal is its SRW and, unless growth is interrupted by under-nutrition, the normal weight of a growing animal follows Brody (1945) and Taylor (1968):

$$N = SRW - (SRW - W_{birth}) \exp\left(\frac{-C_{N1}A}{SRW^{0.27}}\right) \quad (1)$$

where A is the age of the animal (in days) and W_{birth} is weight at birth.

In SCA (1990), the constant C_{N1} has the value 0.0157 for both sheep and cattle, but in this report a value of $C_{N1}=0.010$ is proposed for cattle (see page 10). To accommodate animals with interrupted growth, normal weight is defined generally as the lesser of the value estimated from equation 1 and the highest W attained so far in the life of the animal.

"Relative size", Z , is defined as the ratio of N to SRW , and relative condition, BC , as the ratio of current W to N .

Mortality submodel

The proportion of animals that die on each day is predicted (equation 2) from a basal rate, C_{D1} . There is an additional, condition-dependent, component if body condition, and daily weight gain in the case of growing animals, are below nominated thresholds. The mean base weight of the surviving animals is increased, on the assumption that the animals that died were 10% lighter than the mean of the group.

$$MR = \begin{cases} C_{D1} + C_{D2} \max(0, C_{D3} - BC) & \delta W < 0.2 \frac{dN}{dA} \\ C_{D1} & \text{otherwise} \end{cases} \quad (2)$$

Values used for the parameters are $C_{D1}=2.8 \times 10^{-5}$, $C_{D2}=0.5$ and $C_{D3}=0.6$. Note that equation (2) is applied to the animals on a daily basis, so that in order to use it to estimate total mortality over a year, the pattern of live weight change of the stock should be known (especially the length of time that

animals spend below the critical body condition C_{D3}). The tests of the model described later in this report are, therefore, of necessity indirect.

Conception rate submodel

The GRAZPLAN conception equations predict conception rate as conceptions per head per oestrus cycle. A predicted conception rate includes only those embryos that survive to the third trimester.

Conception rates are modelled as a function of time of year (in the case of sheep) and of the relative size and body condition of the animals. The main equation (4) gives the probability of an animal conceiving at least a given number of young; the probabilities of conceiving specific numbers of young are then obtained by subtraction. The starting point for this equation was a sheep fertility model of F.H.W. Morley developed further in White *et al.* (1983). In its present formulation, the model has been simplified to produce a general function applicable to sheep or cattle. The parameters which have been used to date in these equations are given in Table 1.

$$CR_{\geq 0} = 1 \quad (3)$$

$$CR_{\geq n} = \left(1 - C_{F1} \left[1 - \sin \left(\frac{2\pi}{365} (DOY + 10) \right) \right] \right) \text{SIG}(ZBC, C_{F2n}, C_{F3n}) \quad (4)$$

$$CR_n = CR_{\geq n} - CR_{\geq n+1} \quad (5)$$

where

$$\text{SIG}(x, a, b) = \frac{1}{1 + \exp \left(- \left(\frac{2(\ln(0.95) - \ln(0.05))}{b - a} \right) \left(x - \frac{a + b}{2} \right) \right)} \quad (6)$$

Table 1. Initial parameterization of the GRAZPLAN conception rate equations.

Description			Merino Sheep	Crossbred Sheep	Cattle
C_{F1}	Time of year		0.3	0.3	0.0
$C_{F2,Y}$	5% conception	1 young	0.2	0.2	0.5
		2 young	0.7	0.5	
$C_{F3,Y}$	95% conception	1 young	1.1	1.0	1.0
		2 young	1.5	1.3	

DATA SOURCES

Temperate Australia – sheep

Reproduction data (weight at joining and lambs per ewe joined) were taken from a variety of studies in the literature, as set out in Table 2. The locations of the research stations where the trials were carried out are shown on Figure 1. A total of 14,356 ewe-years were available for analysis. There were sufficient data to fit the model for two ewe breeds, namely Merinos (of various frame sizes) and Border Leicester-Merino crossbreds.

Very few mortality data were available, since nearly all research studies in southern Australia use supplementary feeding to avoid stock deaths. One data set from a clover sowing rate trial by Williams (1978) was located and analysed. This experiment followed the weights of sheep under nutritional stress, and recorded the resulting number of mortalities.

Table 2. Sources for sheep reproduction data – temperate Australia. Standard reference weights assumed for each breed (in kg) are given in brackets.

Reference	Ewe breeds	Joining times	No. years	No. data points	Average lambs/ewe joined
Brown (1977)	Merino (55)	Feb	5	5	1.13
Curll <i>et al.</i> (1975)	Crossbred (55)	Apr	1	3	1.28
Davies (1962)	Merino (45)	Nov, Jan, Mar	2	18	0.80
Donnelly <i>et al.</i> (1982)	Merino (42)	Feb	3	3	1.29
	Crossbred (55)	Feb	3	3	1.73
Dun <i>et al.</i> (1960)	Merino (40)	Sep, Oct, Mar	1	10	0.97
Egan <i>et al.</i> (1977)	Merino (40)	Apr, May	4	6	1.06
Freer <i>et al.</i> (1994)	Crossbred (55)	Feb, Mar	3	12	1.15
Fletcher <i>et al.</i> (1970)	Crossbred (55)	Dec, Mar	1	4	0.90
Killeen (1967)	Crossbred (50)	Dec	2	8	0.96
Reeve & Sharkey (1980)	Crossbred (55)	Dec, Feb, Mar	4	16	1.22

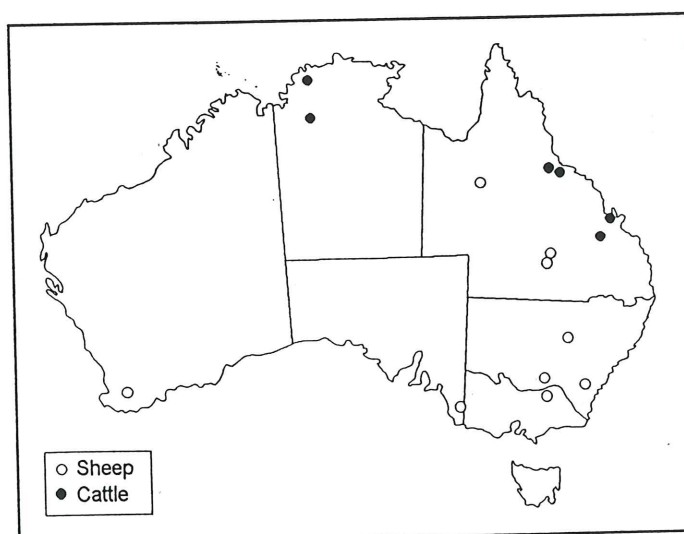


Figure 1. Sites from which biological rate data for sheep and cattle have been taken.

Northern Australia – sheep

Data were drawn from two studies, one from Toorak Sheep Field Research Station in north-west Queensland and the other from a number of properties in south-west Queensland. Both studies dealt with Merino ewes grazing extensive Mitchell grass (*Astrebla* sp.) pastures. The location of the sources of data are shown in Figure 1.

Toorak. Comprehensive records were available on reproduction and mortality, body weight at pre-joining, post-joining, pre-lambing and marking together with greasy fleece measurements at shearing in June (Rose 1972, 1974, 1976, 1978, 1982). Cohorts of animals could be identified by age. Ewes were joined in spring, following normal practice in north-west and central west Queensland.

South-west Queensland. As part of a study on reproductive wastage to lamb marking Jordan *et al.* (1989) kept reproduction and body weight records on eight commercial flocks. Animals were distinguished each year by age and property. In south-west Queensland, ewes are joined in autumn.

There were 72 cohorts from Toorak, ranging in size from 3 to 144 animals, and eight cohorts from south-west Queensland ranging from 98 to 479 animals.

Northern Australia – cattle

Data were taken from six studies, conducted by various organisations. These studies were largely designed as formal statistical trials, incorporating treatments such as breed comparisons and levels, sire effects, differing managerial and nutritional systems. In addition to these primary comparisons, some data have been used for secondary purposes, such as integration within sites to identify groups of "at risk" animals for preferential treatment (Fordyce *et al.* 1990), to investigate alternate culling strategies (O'Rourke 1994), and to evaluate the likely returns from herds of different breeds (Rudder *et al.* 1992). The locations of the six research stations are shown in Figure 1.

The data sought from each trial were performance of groups of animals, on a four-way interaction basis (year by breed by age by lactation status). These were variously available from published sources and theses, unpublished summaries and memos, computer print-outs of analyses, and re-analyses of raw data. In some instances only compressed data (summarised over one of the desired dimensions) were available, and used. Whilst the timing varies, all sites generally experience favourable (wet) and unfavourable (dry) periods each year. Mustering and data collection dates varied with site, but where possible animal weights at approximately the start and end of these periods were obtained also allowing estimation of average weight changes during these periods.

Kidman Springs. These data appear in Sullivan *et al.* (1992) as main effects, but were extracted as the full interaction means. This led to low cell numbers for some classes, so four classes were deleted (totalling eight animals) and some age classes were pooled to give $n > 9$ in each class (except for one observation which was left with six animals).

Mt Bunday. Data were extracted from O'Rourke (1994), where age and lactation status were condensed into five classes: heifers (i.e. two years old, first mating), three-year-old lactating, mature lactating, aged lactating, and non-lactating matures (greater than two years old). The overall average weight change during the wet season was (just) negative in this data set, reflecting both the harsher environment and the fact that many of these animals were lactating through this period, and unable to gain weight (although their calves were).

Fletcherview. Data from the James Cook University Tropical Veterinary Research Station at Fletcherview were available from Anderson (1989). Ages were condensed to three-year-olds and mature animals, with both lactating and non-lactating groups within each.

Swan's Lagoon. Data for the various animal classes were extracted from Anderson (1989), Holroyd *et al.* (1990a & b) and O'Rourke (1994). Reproductive and weight data were available on a year by breed by age/lactation basis, with the last factor condensed into six classes: heifers, three-year-old lactating,

three-year-old non-lactating, four-year-old lactating, greater than four-year-old lactating, and greater than three-year-old non-lactating. Mortality data were only available for lactating animals on a year by breed basis. As analyses of age effects (O'Rourke 1994, p. 183) indicated few important of consistent differences between ages, pooled mortality rates (across ages) were used.

Belmont. Although these studies ran from 1957 to 1984 (Mackinnon *et al.* 1989), animal weights were only readily available for the drought year of 1969 (Frisch 1973). Mortality and calving rate were listed by breeds, being averaged across ages and lactation status. Pregnancy rate (not reported) was back-estimated from calving rate by using breed-specific differences from the comprehensive Brigalow data set.

Brigalow. Pregnancy rate and weight data are listed in O'Rourke *et al.* (1992), by year and breed with age/lactation status condensed into four classes: heifers, three-year-old lactating, greater than three-year-old lactating and greater than two-year-old non-lactating. Weaning and calving rates were estimated on this three-way basis from the least-squares constants of the three two-way fitted interactions from the non-orthogonal analysis of variance (the three-way interaction was unfittable, but unlikely to be important given that the two-way interaction mean squares were on average ten and eight times smaller than those of the three main effects, for weaning and calving rates respectively).

The Kidman Springs trial operated under continuous mating, starting with non-pregnant animals in June of each year. Pregnancy within twelve months was defined as a "success", but calving would have been some time after this if mating occurred late in the year. All other sites experienced controlled mating (generally coinciding with the "wet" period, early in the year). Animals found to be pregnant then calved later that year, setting up an approximately annual cycle.

Overall descriptions of available data (means and ranges) and treatment descriptions for each site are listed in Table 3. The 283 observations in the full data set total over 17 000 cow-years, giving an average of 60 animals per yearly group. Typical data for these year x site x breed x age x lactation status cohorts are illustrated in Figure 2.

The data in Table 3 indicate the range of production systems across the targeted region. Annual mortality rates in the more favourable environments average around 3%, but range up to 12%. At Kidman Springs, however, 11% is the average, with a much greater range. The Northern Territory sites also have lower conception rates, weights and weight gains, due to the harsher conditions. These trends, along with the partial confounding of sites with breeds (only *Bos indicus* – nominally "Zebu crosses" – at the harsher environments, and none of these at Brigalow) cause problems with the analyses. Table 4 shows the correlations between the variables in the cattle data set.

Table 3. Summary of the northern Australian cattle data set.

	Kidman Springs	Mt Bunday	Fletcher- view	Swan's Lagoon	Belmont	Brigalow
Years	1981-89	1980-84	1981-87	1972-86	1969	1980-85
Breeds ^a	Zx(F _N)	Zx(F _N)	Zx(F _N)	Zx(F ₁ ,F _N)	Zx,Ax,Br	Ax,Br,Eu
Observations (cow-years)	3,570	3,590	1,010	5,700	430	2,790
Mortality (%/annum)						
-mean	11.3			2.5	3.2	2.3
-range	0 - 25.6			0 - 6.7	1.5 - 6.0	0.3 - 11.8
Conception Rate (%/annum)						
-mean	59	64	73	74	56	76
-range	4 - 100	13 - 97	7 - 100	8 - 100	50 - 62	12 - 100
Conception Rate (%/cycle)						
-mean	10	20	32	31	30	38
-range	1 - 28	2 - 45	2 - 60	2 - 62	26 - 34	4 - 65
Calving Rate (%)						
-mean					51	65
-range					45 - 57	12 - 100
Weaning Rate (%)						
-mean	42			55		61
-range	3 - 92			0 - 86		12 - 100
Weight ^b (start mating) (kg)						
-mean	270	353	387	348		419
-range	177 - 326	298 - 374	267 - 487	213 - 454		287 - 594
Weight (end of wet)						
-mean	319	333	437	393	435	459
-range	223 - 404	258 - 410	296 - 522	268 - 498	423 - 443	330 - 643
Weight (end of dry)						
-mean	322			366	378	
-range	250 - 426			270 - 482	354 - 392	
Wet season weight change (kg/month)						
-mean	9.1	-0.1	13.7	18.8	18.8	17.3
-range	-3.4 - 25.4	-6.6 - 11.8	-2.3 - 27.7	0.4 - 48.8	17.2 - 19.8	-2.2 - 38.3
Dry season weight change						
-mean	-5.4			-0.1	-7.3	
-range	-17.6 - 8.4			-10.5 - 15.0	-8.7 - -6.0	

(a) Zx = Zebu crosses; Ax = Africander crosses; Br = British breeds; Eu = European breeds;
F = filial generation.

(b) All cow weights are adjusted for conceptus products.

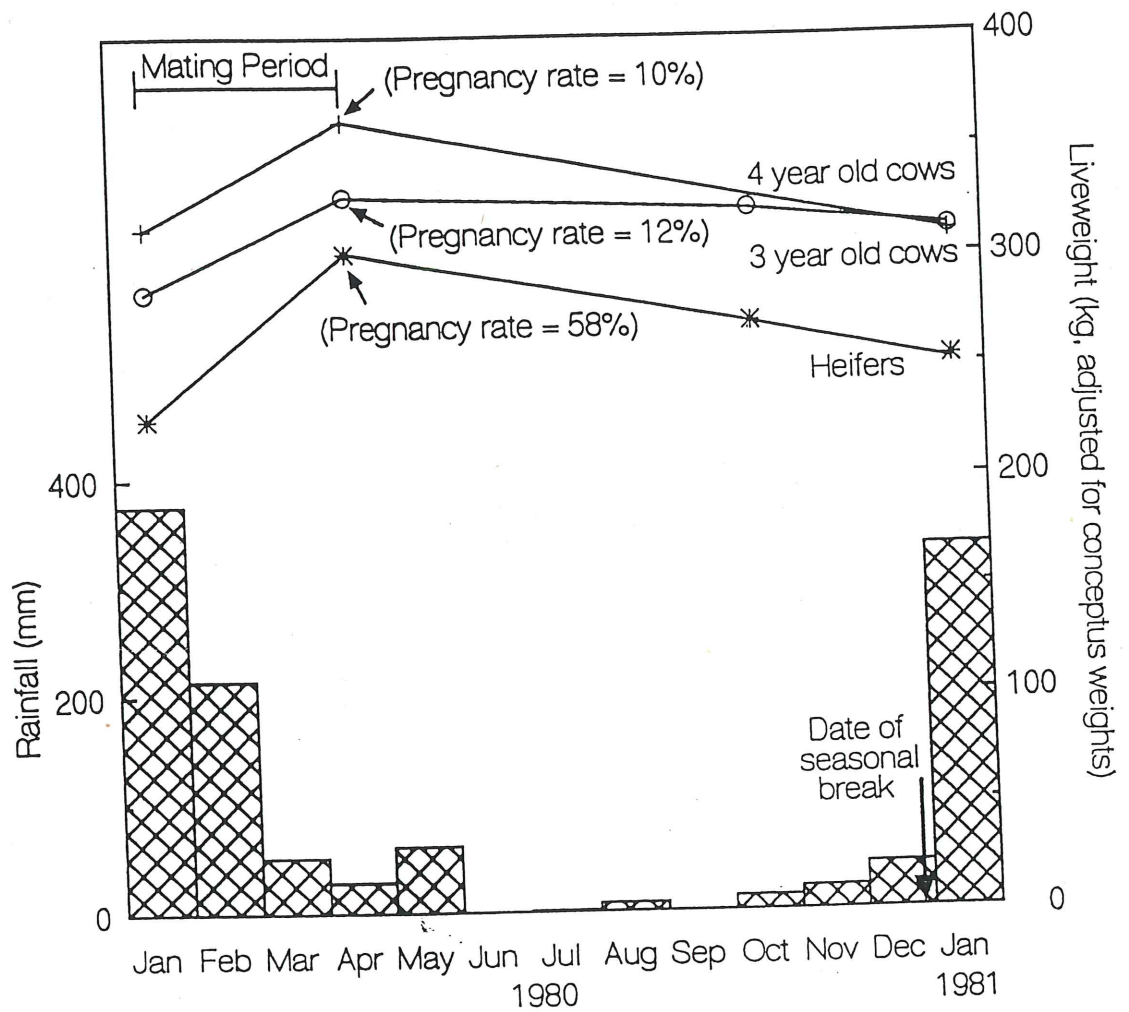


Figure 2. A sample of the northern Australian cattle data set. Data from 1980-81 for three age cohorts of F_1 Zebu crosses at Swan's Lagoon

Table 4. Degree of dependence (R^2 , as percent) amongst predictor variables in the northern Australian cattle data set. Bold entries indicate significant correlations ($P < 0.01$).

	Age	Lactation Status	Start Weight	"Wet" Weight	"Dry" Weight	Change (wet)	Change (dry)	Change (annual)
	<i>A</i>	<i>L</i>	<i>W_{start}</i>	<i>W_{wet}</i>	<i>W_{dry}</i>	ΔW_{wet}	ΔW_{dry}	ΔW
FACTORS								
Breed	3.1	0.1	34.6	36.2	7.0	2.2	3.7	4.2
Year	8.1	0.1	21.8	17.1	19.7	27.9	19.0	49.5
Year Type	0.1	1.2	3.4	2.9	4.0	3.9	7.3	5.3
Site	16.1	1.4	47.3	48.9	9.9	19.7	16.5	1.0
VARIATES								
Age	—	8.2	6.9	11.3	10.0	4.6	3.2	3.2
Lact. Status		—	2.0	7.5	12.9	23.7	8.8	30.8
Start Wt.			—	85.4	26.3	2.3	5.3	10.9
"Wet" Weight				—	43.9	6.9	1.8	0.3
"Dry" Weight					—	11.1	46.7	24.7
Change (Wet)						—	18.1	16.1
Change (Dry)							—	45.1

METHODS OF ANALYSIS

Estimating conceptus-free live weight

All animal weights were adjusted for weight of the conceptus and products as necessary. For cattle, the corrections applied were either via the method of O'Rourke *et al.* (1991) for the specific breeds covered by him, otherwise the similar, general relationships of Silvey and Haydock (1978). When applied in a practical sense to estimating cow weights, the differences between these methods are insignificant (P.K. O'Rourke, *pers. comm.*).

For the Queensland sheep data sets, weight of the conceptus was estimated using the equations of Langlands and Sutherland (1968). Langlands and Sutherland's basic equation was scaled using the ratio of birth weight to their prediction of foetal weight at birth, resulting in equation 7:

$$W_C = \frac{W_{birth}}{9.11g - 0.349g^2 + 0.00343g^3} (0.0358(t-4)^{2.43}) \quad (7)$$

where g = gestation length (days)
 t = time from mating (days)

Average birth weights and gestation lengths were available for the Toorak data set; a birth weight of 3.5 kg and a gestation length of 149 days were assumed for south-west Queensland (Jordan, *pers. comm.*).

Live weights in the Toorak and temperate sheep data sets were corrected for measured mean greasy fleece weights on a pro-rata time basis. In the south-west Queensland data set, the shire average greasy fleece weights for the year were used.

Estimating conception rate from pregnancy records

The quantity examined for both sheep and cattle was the probability that at least one young would be conceived, $CR_{\geq 1}$ (henceforth CR). There were insufficient data to test the predictions for multiple conceptions in the northern sheep data set, but in the temperate sheep data set, the model for $CR_{\geq 2}$ was also examined.

Data were obtained as pregnancy rates (PR), which were not immediately comparable between sites or with the GRAZPLAN equation because of differing lengths of mating periods. For example, pregnancy rate is higher in the continuously-mated Kidman Springs trial than at other cattle trials with controlled mating, simply because cows at Kidman Springs had more opportunities (cycles) to achieve pregnancy. To standardise, conception rate per cycle was calculated as:

$$CR = 1 - (1 - PR)^{1/n} \quad \text{where } n \text{ is the number of cycles} \quad (8)$$

This is a probabilistic calculation, and the discreteness of the binary response causes problems when all animals get pregnant in the period (as occurred with 12 cohorts of cows, averaging 12 animals per cohort). The calculated CR is then also 100%, implying all animals get pregnant each cycle, which is unrealistic. Graphically, these points were far removed from the rest. Rather than delete these points (as they are valid representations), we nominally deleted "quarter of a cow" from PR for the CR calculation. This adjustment is based on the view that the "all pregnant" result would not have been observed if there had been a larger number of animals in that cohort, and that an observation of n animals falling pregnant in a cohort of size n covers the range from " $(n-0.5)$ animals pregnant" to " n animals pregnant". The half-way point in this range, namely $(n-0.25)$, has been adopted as its representation. For example, with 12 animals in the group and 3 cycles, 11.75 are deemed to be pregnant, and the estimated CR becomes $1 - (1 - 11.75/12)^{1/3} = 72\%$. This change to a more realistic

Table 5. Predictor variables used in statistical analyses of the northern Australian data sets.

Predictor	Cattle		Sheep	
	Mortality	Reproduction	Mortality	Reproduction
Site (see Table 3)	x	x	x	x
Breed (see Table 3)	x	x		
Year type ¹	x	x		
Age	x	x	x	x
Lactation status	x	x		
"Age & lactation status" ²	x	x		
Proportion pregnant	x		x	
Weights (various times)	x	x	x	x
$BC_{0.0157}^*$ (various times)	x	x	x	x
$BC_{0.01}^*$ (various times)	x	x		
Weight change	x	x	x	x

interpretation shifted these values to around the top of the scattergrams. With the low weighting of these observations, the change had little effect on the degree of fit.

For the temperate sheep data set, $CR_{\geq 2}$ was estimated from PR and the proportion of ewes conceiving multiple lambs ($PR_{\geq 2}$) as:

$$CR_{\geq 2} = PR_{\geq 2} / PR \quad (9)$$

Predictor variables and factors

For the temperate data sets, only the predictors in the GRAZPLAN models (breed, Z and N) were used. For the northern Australian data sets, the predictors which were considered are set out in Table 5.

Because of the low frequency of weight measurements of cattle in the northern Australian trials, BC was estimated as W/N , where N was computed with equation (1). These estimates of BC are the best available, but they do not take into account the effect of interrupted growth on N . For the cattle analyses, there are two estimates of BC ($BC_{0.0157}^*$ and $BC_{0.01}^*$) corresponding to the two proposed values of C_{M1} .

Estimating standard reference and normal weights

To fit the GRAZPLAN models, the breed-specific parameter SRW (standard reference weight) and the animal-specific variable N (normal weight, equation 1) must be determined. SRW cannot be estimated from the data points alone; including it as a parameter when fitting either of the GRAZPLAN submodels numerically results in redundancy amongst the parameters, and consequently in meaningless results.

For the northern Australian data sets, SRW was taken to be 520 kg for cows of European breeds, 425 kg for cows of other breeds and 40 kg for Merino ewes. In the southern Australian data sets, SRW was assigned the values in Table 2 (generally following SCA 1990). For the large Merinos of the Williams (1978) data set, SRW was estimated as 60 kg.

Calculation of the normal weights N proved to be more contentious. Brody (1945) theorised an exponential curve describing weight gain from birth to maturity, based on weight raised to a power of 0.27. Taylor (1965, 1968) further developed this model, tabulating potential growth rates by species of

¹ A nominal good, average or poor, based on rainfall deciles within sites.

² Heifers, three-year-old lactating, greater than three-year-old lactating and non-lactating

animal. The tabulated value for sheep of 1.8 back-converts to a C_{M1} (the growth rate) of 0.0157, as used in the GRAZPLAN equations. However, for cattle the tabulated values convert to a C_{M1} of 0.008 to 0.01, indicating slower proportionate growth. It may be argued that skeletal growth in cattle ceases at around four years, and that the more rapid potential growth using $C_{M1}=0.0157$ is appropriate. Conversely, slower growth of cattle in this environment may reasonably be expected – an exponential model fitted to the observed weight data of Table 3 (ignoring all other factors) estimated C_{M1} as 0.0104 (standard error 0.006), indicating a value of 0.01 as reasonable. For analyses, both values were considered and tested.

For estimating conception rates, the decision of which C_{M1} to use in the calculation of N is not an issue as the $Z.BC$ term reduces to W/SRW , and is hence independent of N .

Fitting the GRAZPLAN models

The fit of the GRAZPLAN equations was assessed using the coefficients given in Table 1, and then the equations were re-parameterized by fitting coefficients. In the cattle data set, a common parameterization over all breeds and separate coefficients for three breed types (British breeds, European breeds and others) were tried. In addition, specific generalisations of the GRAZPLAN equations were fitted, as discussed in the Results section. For the northern data sets, calculated CR values were fitted to the model within the GENSTAT statistical package using Newton's method. Because the temperate data set included substantial rates of twin births, and because estimated $CR_{\geq 2}$'s had to be constrained to be less than estimated $CR_{\geq 1}$'s, the GRAZPLAN equations were fitted to the temperate sheep PR data using the function-minimization feature of Microsoft Excel.

Statistical analyses

The northern Australian data sets were also analysed statistically. General linear models (of both discrete factors and continuous variates) were fitted to the dependent variates.

As a considerable portion of the mortality data was in the 0 to 5% range, it was inappropriate to assume a normal distribution of sampling errors. General linear models were therefore fitted via analysis of deviance, using a binomial error distribution and logit link function. Conception and pregnancy rates were generally above 10%, and so the general linear models for these data were fitted by analyses of variance using a normal error model. Binomial model with logistic link functions were tried but produced almost identical results, so the normal was preferred on grounds of simplicity.

Models were determined by using the step-forward method of successively including the next best predictor. In all analyses, the number of observations (cow-years or ewe-years) in each cohort or cell was used as a weighting factor.

The statistical analyses struck problems with correlations amongst the "independent" variates, as shown for cattle in Table 4. The highest dependencies (as may be expected) are amongst the weight variables. Mostly measured at different times of the year, these are auto-correlated, and so only one of these terms may be fitted in any model. As mentioned earlier, site is correlated with a number of the predictor variables, indicating partial confounding and introducing a degree of uncertainty into interpretation. Weight changes also tend to be correlated with weights, despite both being important predictors of animal wellbeing and hence performance.

RESULTS – MORTALITY

Temperate Australia - sheep

Starting weights, rates of weight loss and numbers of deaths were taken for three of the most stressful treatments in Williams' (1978) sowing rate experiment, and the GRAZPLAN mortality equation applied iteratively to compute the expected number of surviving wethers (from 10 initially). The results are shown in Figure 3; the GRAZPLAN equation does a respectable job of predicting the mortality rate.

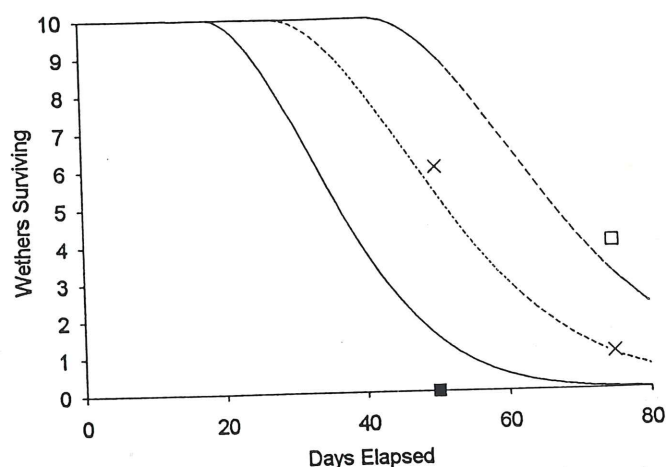


Figure 3. Predicted and actual death rates in a clover sowing rate trial of Williams (1978). —■ 1 kg/ha;× 4 kg/ha;□ 8 kg/ha.

Northern Australia - sheep

Mortality rates for the period from pre-joining to marking were not well estimated by the GRAZPLAN equation, as the minimum relative condition did not fall below the critical relative condition. Estimates of mortality thus reduced to a constant.

The screening analysis (Table 6) showed that minimum relative condition (BC_{min}) over the year was a better single predictor than minimum weight and hence BC_{min} was included in subsequent models. A model with BC_{min} , age, pregnancy rate, and the interaction between pregnancy rate and BC_{min} explained 78% of the variation:

$$AMR = \frac{1}{1 + e^{-y}} \quad (10)$$

$$y = 14.51 + 0.20A - 22.41BC_{min} - 13.07P + 17.59BC_{min} \cdot P$$

where A = age (years)
 BC_{min} = minimum condition at pre-joining, post-joining, pre-lambing and marking
 PR = pregnancy rate (0-1)

If site was included in this model a further 2% could be explained. Mortality rates predicted from the model without site are compared with actual mortality rates in Figure 4.

Table 6. R^2 values (as percent) for predictors of mortality from pre-lambing to lamb marking.

Single variate models:		Final (multiple) model:	
W_{min}	37 ***	BC_{min}	54 ***
BC_{min}	54 ***	+ A	14 ***
A	30 ***	+ PR	3 *
ΔW	0 ns	+ $BC_{min} \times PR$	7 ***
PR	5 ns		78
Site	5 ns		

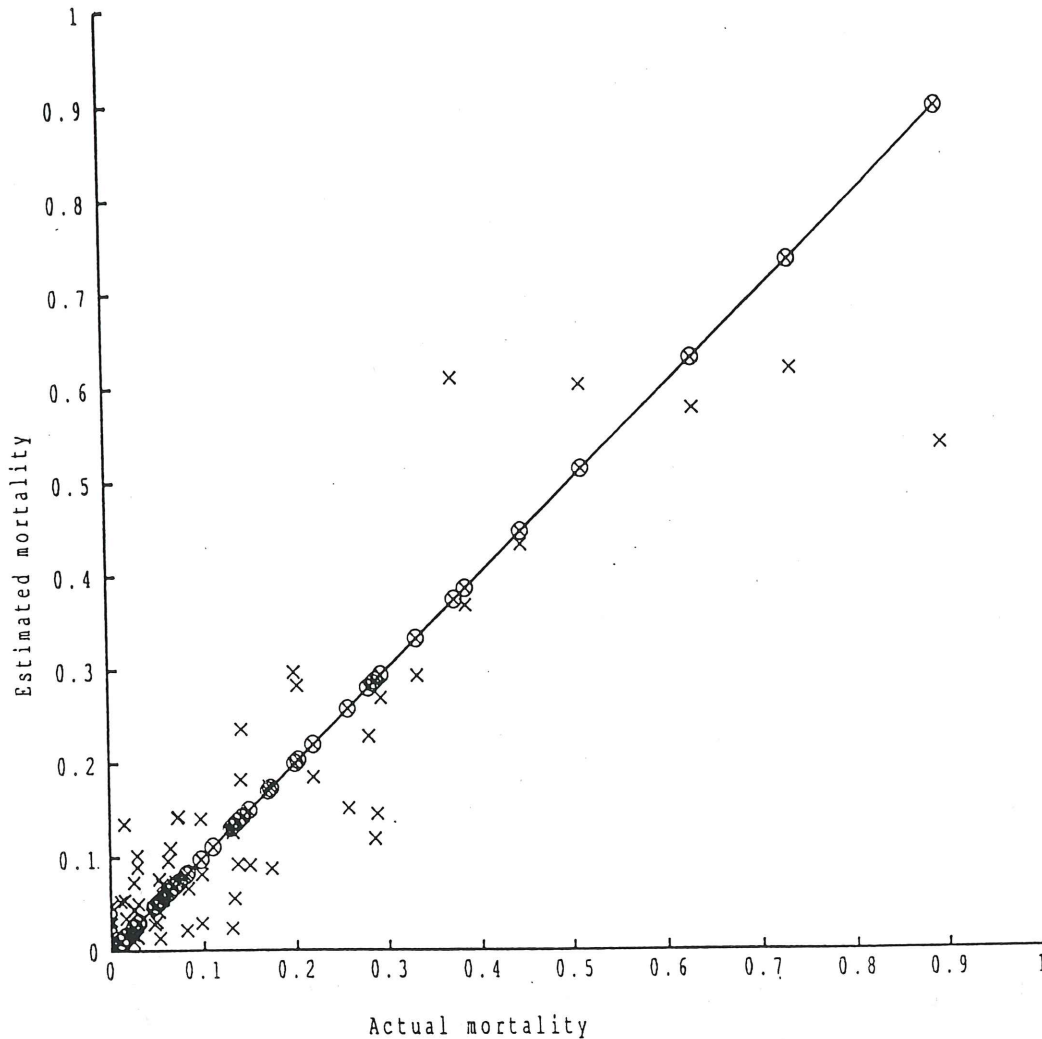


Figure 4. Estimated vs actual mortality rates for the Queensland sheep data set. Estimated mortality rates are from equation (10).

Northern Australia - cattle

For these data, which show a "saw-tooth" weight gain over time (e.g. Figure 2), minimum weight during the year occurs at the end of the dry period. The measured weights only approximate this minimum, because of logistical and planning constraints. The maximum weight for the year (measured at the end of the wet) should be fairly accurate, and in most cases would be the highest weight attained by the animals over their lives. The exception here is where mature animals may be lighter in a drought year (following a good or average year). The ratio of weight at the end of the dry season to weight at the end of the wet season should therefore approximate a cow's minimum value of BC over a year.

This ratio was plotted against age for these data. All values were above the critical BC limit, giving predicted mortality of 1.1% throughout. This compares with a weighted observed mean of 6.7%. Some predictive ability might be obtained if the mature cohorts were traced back to get the true highest historical weights, but the difference between these two figures would not be bridged. At present, no re-parameterization of the GRAZPLAN submodel has been attempted.

Only three sites contributed data covering performance during the dry season (the critical period for mortality; P.K. O'Rourke, *pers. comm.*). Individual term models for these sites are listed in Table 7, along with the four-site models where possible. It is obvious that a range of potential predictors exists.

Table 7. R^2 values for individual predictors of annual mortality in the northern Australian cattle data set.

	With dry period data	Without dry period data
Number of sites	3	4
Number of observations	116	194
Number of cow-years	7,360	10,680
FACTORS		
Site	47.5 **	54.5 **
Breed	5.6 ns	22.8 **
Year type	0.3 ns	0.1 ns
Age & lactation status	37.7 **	23.0 **
VARIATES (quadratic models)		
<i>A</i>	36.3 **	24.1 **
Lactation status	0.3 ns	0.2 ns
<i>PR</i>	2.4 ns	3.0 ns
<i>W</i> - mid-wet	19.7 **	21.6 **
- mid-dry	15.7 **	—
- average	19.2 **	22.0 **
$BC_{0.0157}^*$ - wet	22.0 **	27.2 **
- dry	21.0 **	—
- average	24.7 **	29.3 **
$BC_{0.01}^*$ - wet	29.9 **	35.6 **
- dry	38.1 **	—
- average	41.7 **	42.2 **
ΔW - wet period	9.1 **	10.1 **
- dry period	26.0 **	—
- overall	22.6 **	—
MULTIPLE MODELS		
$BC_{0.01}^* + A$	64.4 **	58.7 **
+ Age & lactation status	63.5 **	57.1 **
+ ΔW (dry)	48.2 **	—
+ <i>PR</i>	44.6 **	47.2 **
$BC_{0.01}^* + A + \Delta W$ (dry)	66.2 **	—
$BC_{0.01}^* + A + \Delta W$ (dry) + $BC_{0.01}^* \times A$	67.3 **	—

Estimated BC is a far better predictor than weight, with the best relationships obtained by using the slower growth rate ($C_{N1}=0.01$) for the calculation of N . Average annual body condition was also consistently better than either wet or dry season body conditions, although with the weight change variables, it was best to use the dry period.

As a check, a tree-based regression was conducted using S-Plus. This is a binary, recursive technique which searches the data for cutoff points which maximise the degree of discrimination for the dependent variable. The resulting tree is shown in Figure 5 (minor branches, largely reflecting clutter or variation, have been pruned). It is evident that $BC_{0.01}^*$ is the dominant effect, and that within this other terms make a reasonable contribution.

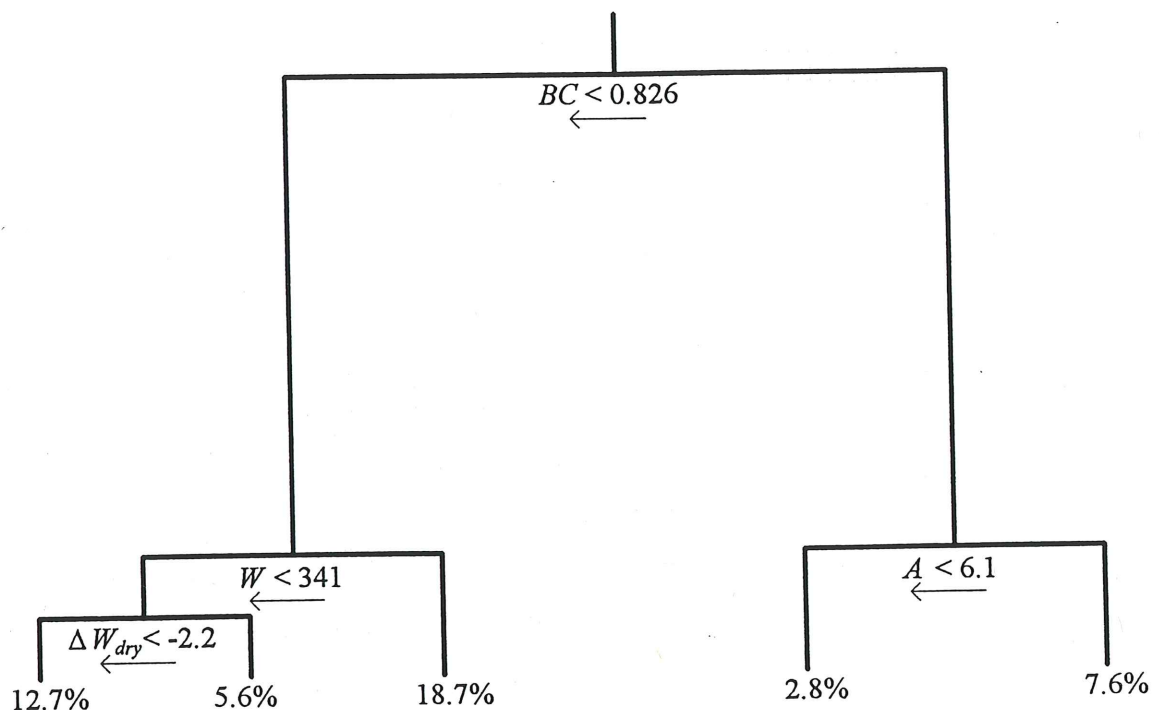


Figure 5. Tree regression diagram for annual mortality in northern Australian cattle. The length of each branch indicates the degree of discrimination.

A step-forward multiple model was then computed with $BC_{0.01}^*$ as the initial term. Age was the next best predictor (Table 7), although all of the four models listed were significant improvements. With age in the model, the "age/lactation status" factor dropped from consideration, and the other terms in Table 7 were sequentially added to the model. The tabulated terms all make biological sense, with "% pregnant" (at the end of mating, earlier in the year) reflecting animals which calve near the end of the dry season, and are therefore lactating through this period of maximal stress. This variate dropped from significance, however, after weight change was added.

As a final step, all multiplicative and divisive interactions of the four fitted terms were screened. The $BC_{0.01}^*$ by age interaction was the only one which was significant, lifting the R^2 to 67% (Table 7). Importantly, with this model the site and breed factors were both non-significant when added, indicating that any site or breed differences are adequately explained by the nominated predictor variables. The final model (Table 7) includes terms which quantify a biologically complex interaction between BC and age, as graphed in Figure 6. The other term, namely weight change during the dry period, was also important. The observed range of weight changes produced a 5.4% variation in annual mortality (back-transformed from the logit, with observations adjusted to their mean values for the other variates).

$$AMR = \frac{1}{1 + e^{-y}} \quad (11)$$

$$y = -21.3 + 40.7 BC_{0.01}^* - 24.2 BC_{0.01}^* + 1.05 A - 0.893 A \cdot BC_{0.01}^* - 0.0255 \Delta W$$

where AMR is annual mortality rate, A is age in years and ΔW is weight change over the dry period in kg per month.

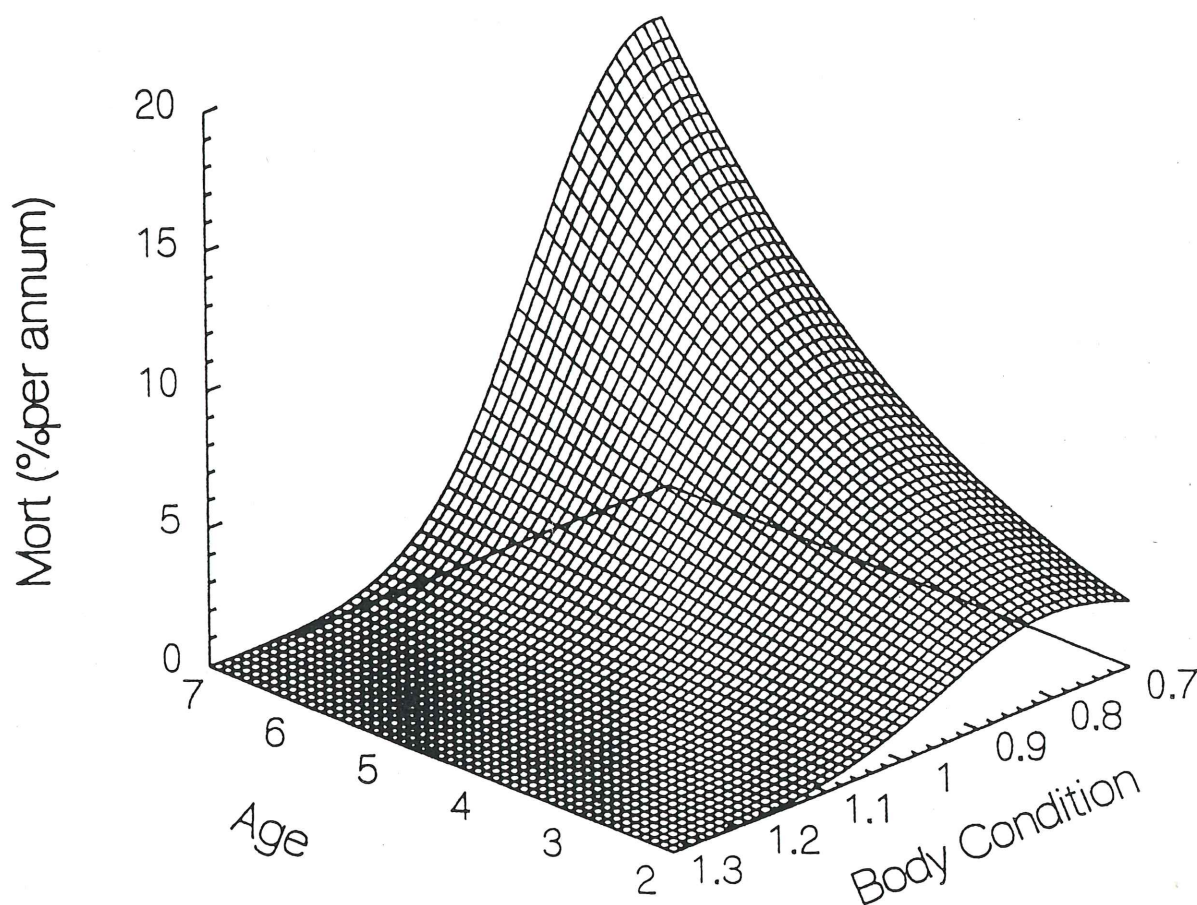


Figure 6. Cattle mortality: fitted surface for age x body condition interaction.

RESULTS - REPRODUCTION

Temperate Australia - sheep

When the GRAZPLAN conception rate model was fitted with the parameters proposed in Table 1 above, it was found not to fit the data very well (for Merinos, the standard error of estimation was 0.26 lambs/ewe, while for crossbreds it was 0.36). This was because the model over-estimated conception rates across the board, especially conception of twins (Figure 7). Fitting new parameters resulted in a considerable improvement for both breeds, especially when the model was generalised to allow time of year to have different effects on $CR_{\geq 1}$ and $CR_{\geq 2}$ (Figure 8; Table 8). As the fit of the GRAZPLAN equations is considered satisfactory, no statistical analyses are presented.

Table 8. Temperate sheep data set: final parameterization of the GRAZPLAN conception rate equations.

Description			Merino Ewes	Crossbred Ewes
$C_{F1,Y}$	Time of year	1 young	0.23	0.34
		2 young	0.39	0.64
$C_{F2,Y}$	5% conception	1 young	-0.62	0.18
		2 young	0.22	0.52
$C_{F3,Y}$	95% conception	1 young	1.90	1.33
		2 young	2.41	1.35
Standard error of estimation (lambs/ ewe)			14%	11%
R ²			57%	84%

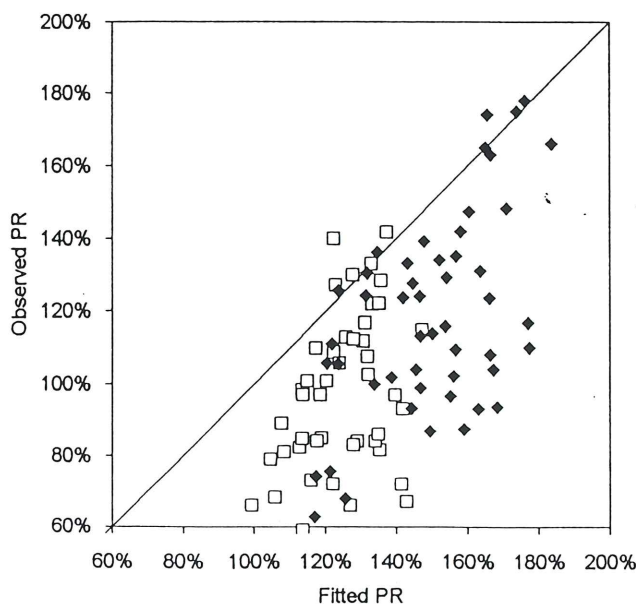


Figure 7. Initial fit of the GRAZPLAN conception equations to the temperate sheep data set. ♦ Merinos; □ crossbreds.

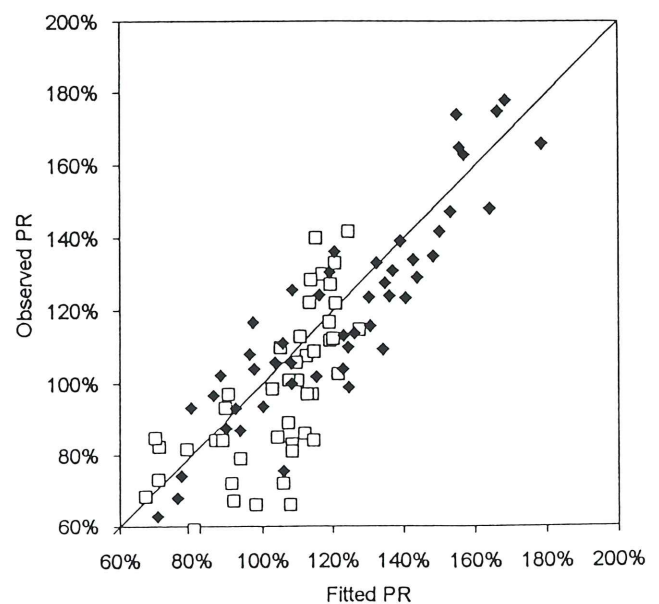


Figure 8. Fit of the GRAZPLAN conception equations after re-parameterization and inclusion of an extra parameter for the time-of-year effect. ♦ Merinos; □ crossbreds.

Northern Australia - sheep

The unmodified GRAZPLAN equations developed with southern data did not estimate the probability of pregnancy well (Figure 9). When the parameters C_{F1} , $C_{F2,1}$ and $C_{F3,1}$ were re-estimated using the Queensland data sets, however, the GRAZPLAN equations together with equation (8) predicted pregnancy rate PR well ($R^2 = 87\%$, $C_{F1} = 0.33$, $C_{F2,1} = 0.60$, $C_{F3,1} = 1.03$; Figure 10).

In this data set, however, the time of joining (spring vs autumn) is completely confounded with site (north-west and south-west Queensland). This gives rise to some concern that a possible difference between north-west and south-west Queensland data is being attributed to the photoperiod effect. No significant differences were found to exist between reproduction from autumn and spring joinings in north-west Queensland by Rose (1976).

If the time-of-year effect was omitted from the GRAZPLAN equations (i.e. C_{F1} set to 0), they still explained 85% of the variation in PR ($C_{F2,1} = 0.58$, $C_{F3,1} = 1.41$).

As the proportion of ewes served is of the order of 100% in southern Australia but sometimes lower than 70% in north-west Queensland, an investigation was conducted of the effect of predicting the proportion served and then the proportion of mated ewes which conceive. Gompertz curves predicted the proportion of ewes served, S , well ($R^2 = 89\%$; Figures 11 and 12):

$$S = \begin{cases} 0.244 + 0.683 \exp(-0.956(W-33.0)) \\ 0.286 + 0.699 \exp(-0.320(W-30.6)) \end{cases}$$

maiden ewes

adult ewes

$$\begin{aligned} & 0.244 + 0.683 * e^{-0.956(W-33.0)} \\ & 0.286 + 0.699 * e^{-0.320(W-30.6)} \end{aligned}$$

The GRAZPLAN equations, with $C_{F1} = 0$, were then fitted to the proportion of mated ewes which fell pregnant per oestrus cycle. The best fit had an R^2 of 61%, with $C_{F2,1} = 0.30$ and $C_{F3,1} = 1.48$. The proportion of mated ewes which fell pregnant was then determined by conception rate of mated ewes per cycle in equation (8). The overall result of this staged process is that 13.8% of the variation in PR is left unexplained (Figure 13).

In an attempt to further improve predictive ability, the second stage (predicting proportion of mated ewes falling pregnant per cycle) was modelled as a generalised linear model with a normal error function. Screening analyses (Table 9) showed BC measured post-joining (BC_{post}) to be a better single predictor than weight or its logarithm, so BC_{post} was used in subsequent models. Unfortunately site was the best single predictor. A model with BC_{post} , age class, and their interaction explained 76% of the variation:

$$CR|mated = \begin{cases} 1.72 BC_{post} - 0.99 & \text{maiden ewes} \\ 1.04 BC_{post} - 0.46 & \text{adult ewes} \end{cases} \quad (13)$$

(When site was included the model explained 84% of the variation.) Equations (13), (8) and (12) were combined to estimate overall PR ; these estimates are compared with the actual pregnancy rates in Figure 14. The estimated unexplained variation in PR from this model was 11.7%.

Table 9. Northern sheep data set: statistical predictors of conception rate of mated ewes per oestrus cycle. Figures are R^2 , given as percentages.

Single variate models:		Final (multiple) model:	
W_{post}	59 ***	BC_{post}	64 ***
$\ln(W_{post})$	58 ***	+ age class	10 ***
BC_{post}	64 ***	+ $BC_{post} \times \text{age class}$	2 *
age class	21 ***		76
ΔW (over joining)	31 ***		
Site	76 ***		

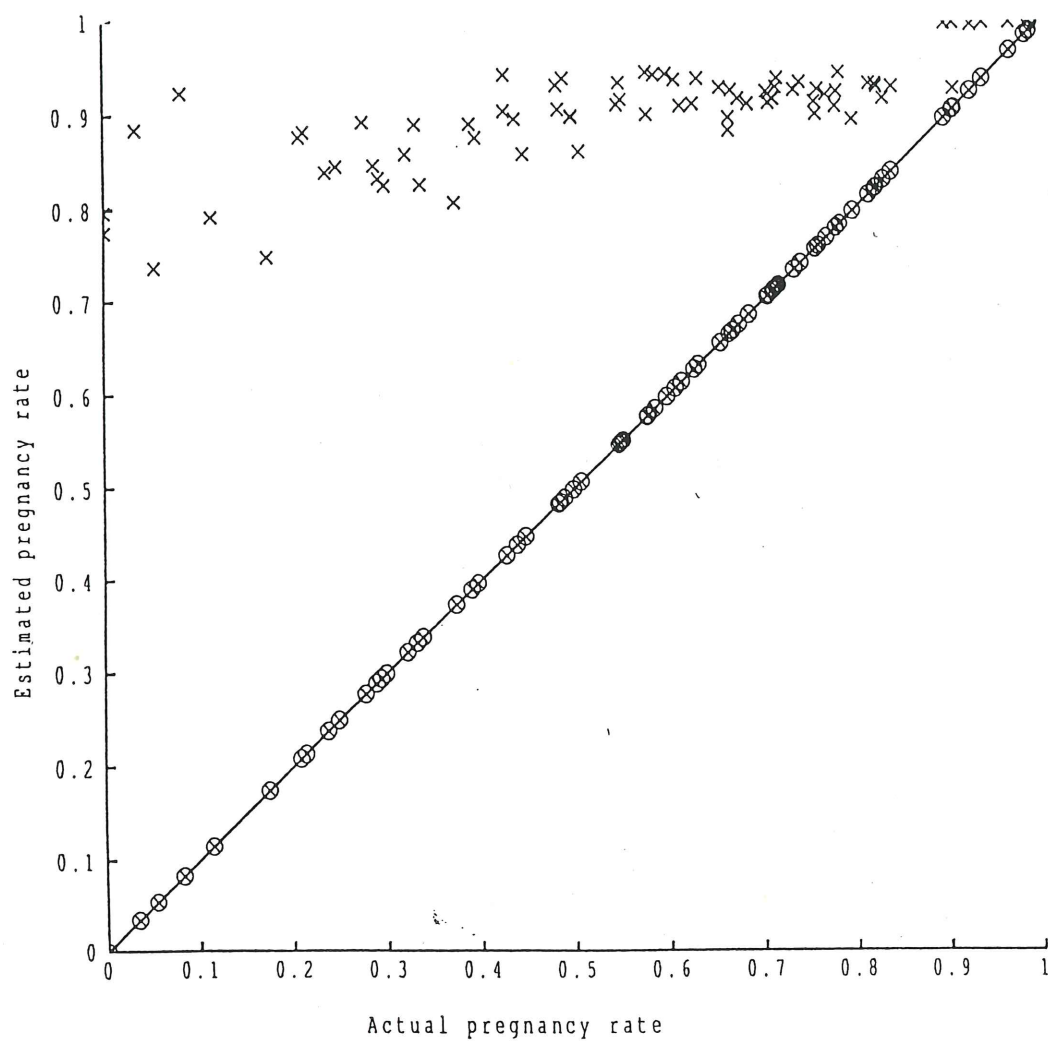


Figure 9. Actual vs estimated pregnancy rates for the Queensland sheep data set, when conception is predicted with the unmodified GRAZPLAN equations.

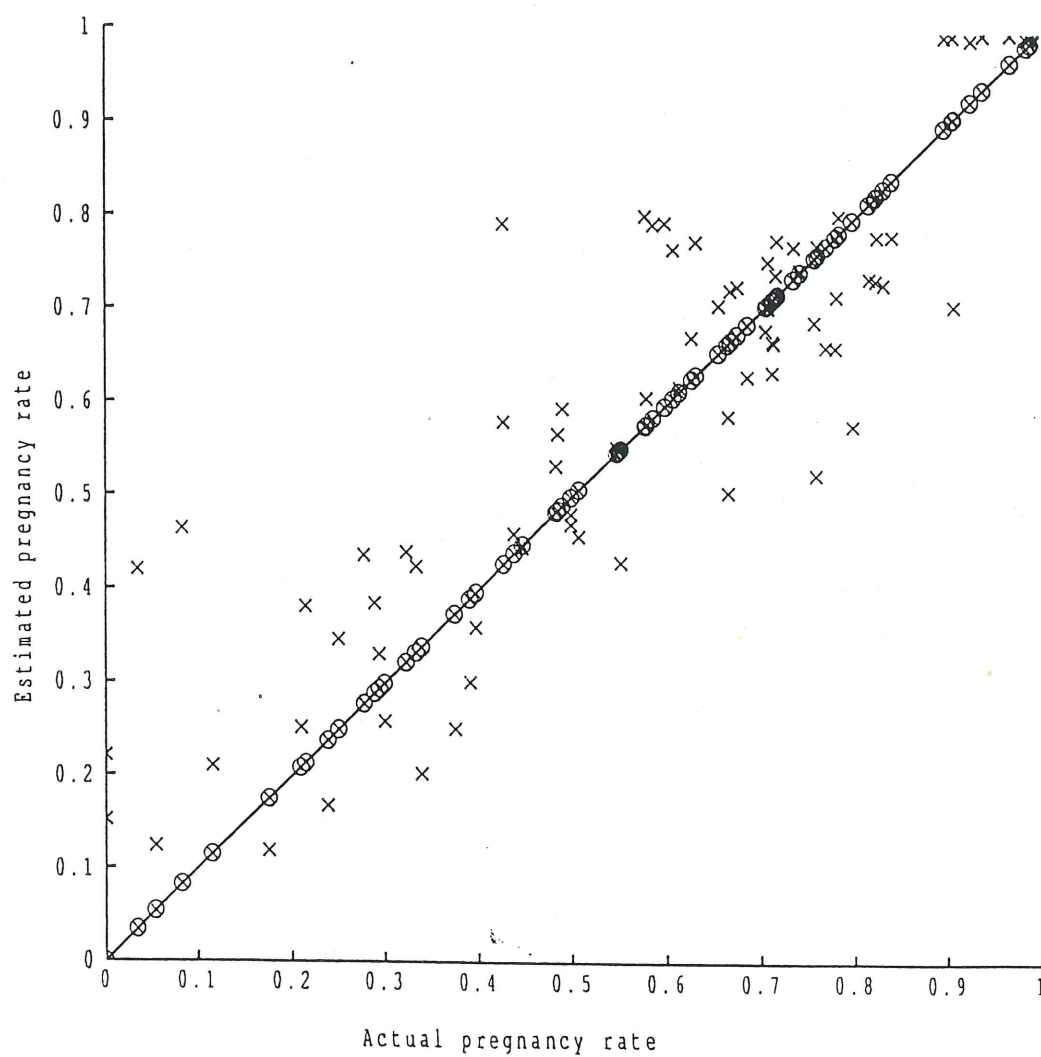


Figure 10. Actual vs estimated pregnancy rates for the Queensland sheep data set, when conception is predicted with the re-parameterized GRAZPLAN equations.

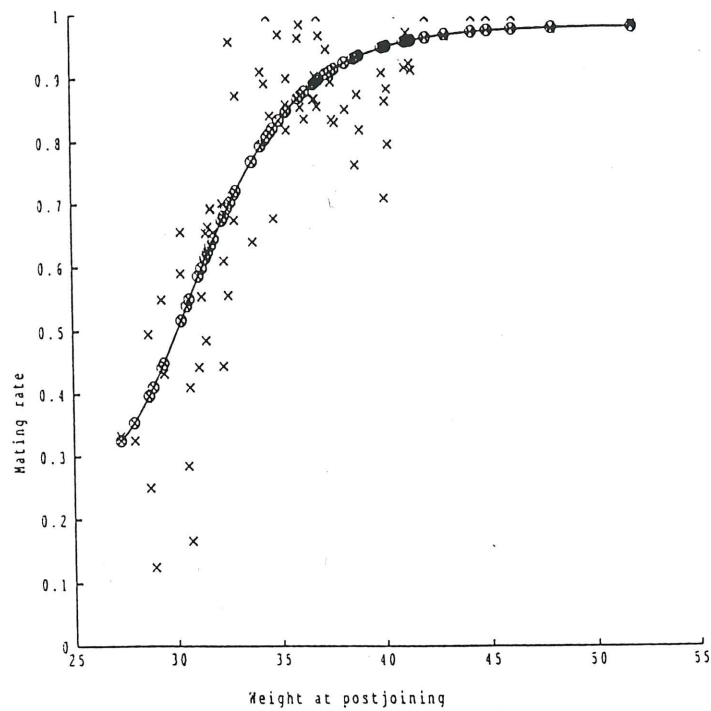


Figure 11. Mating rate for adult ewes in the Queensland sheep data set.
The fitted function is equation (12).

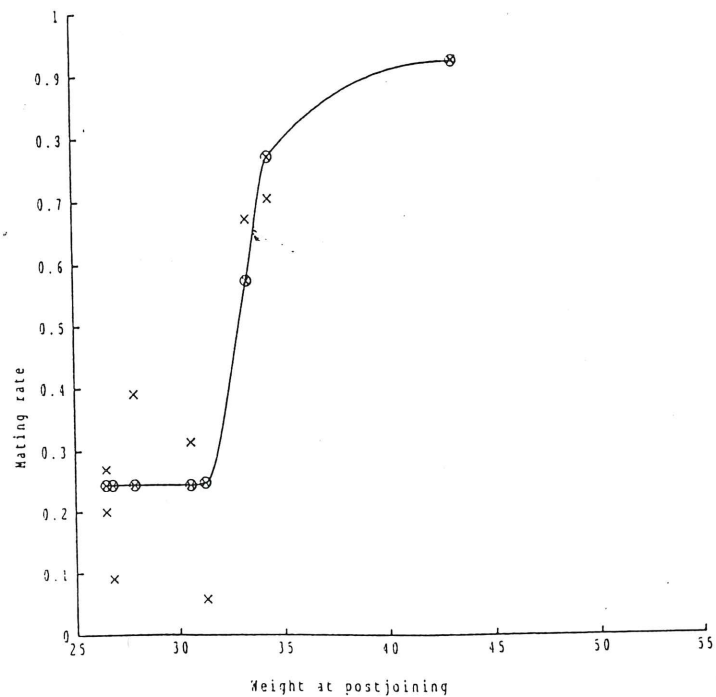


Figure 12. Mating rate for maiden ewes in the Queensland sheep data set.
The fitted function is equation (12).

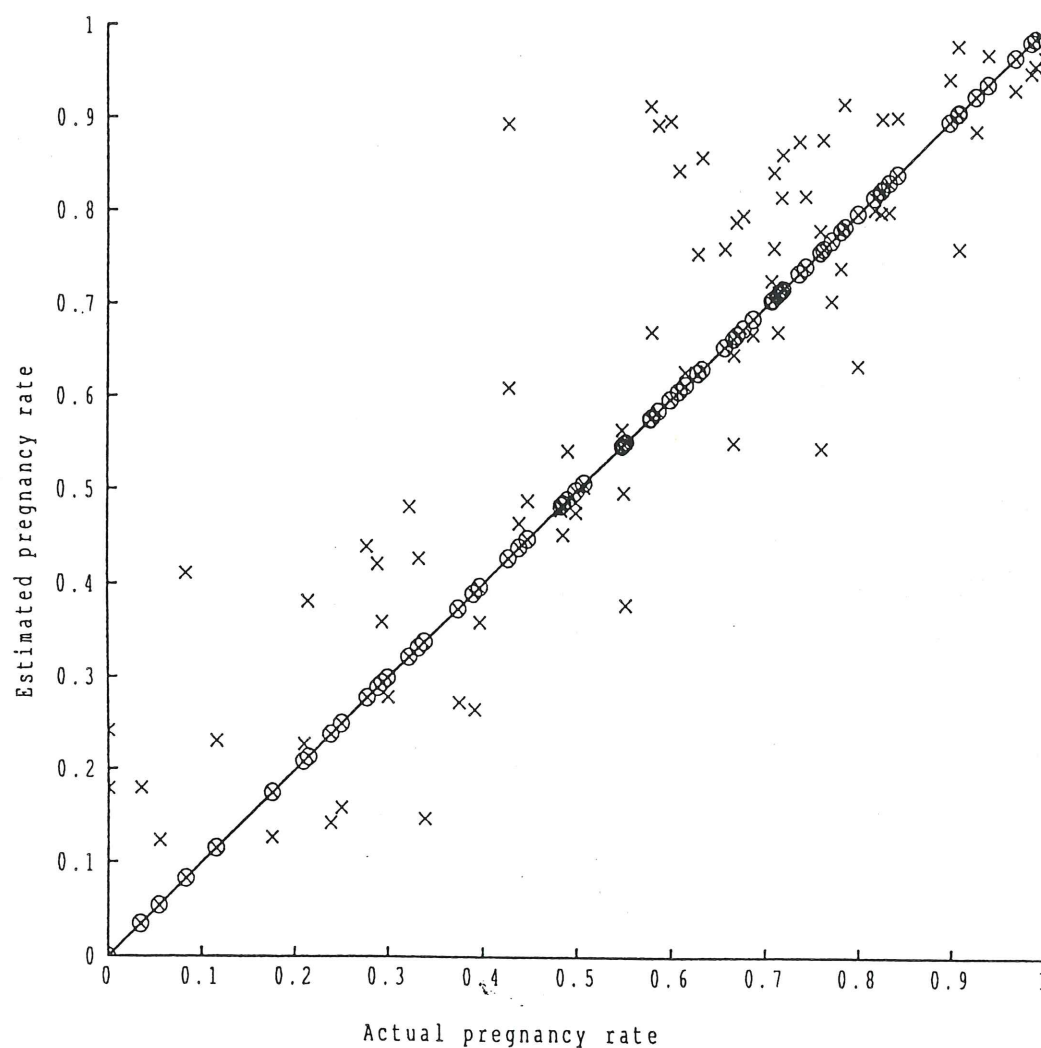


Figure 13. Actual vs estimated pregnancy rates for the Queensland sheep data set, when conception is predicted by a two-stage process combining equation (12) with modified GRAZPLAN equations.

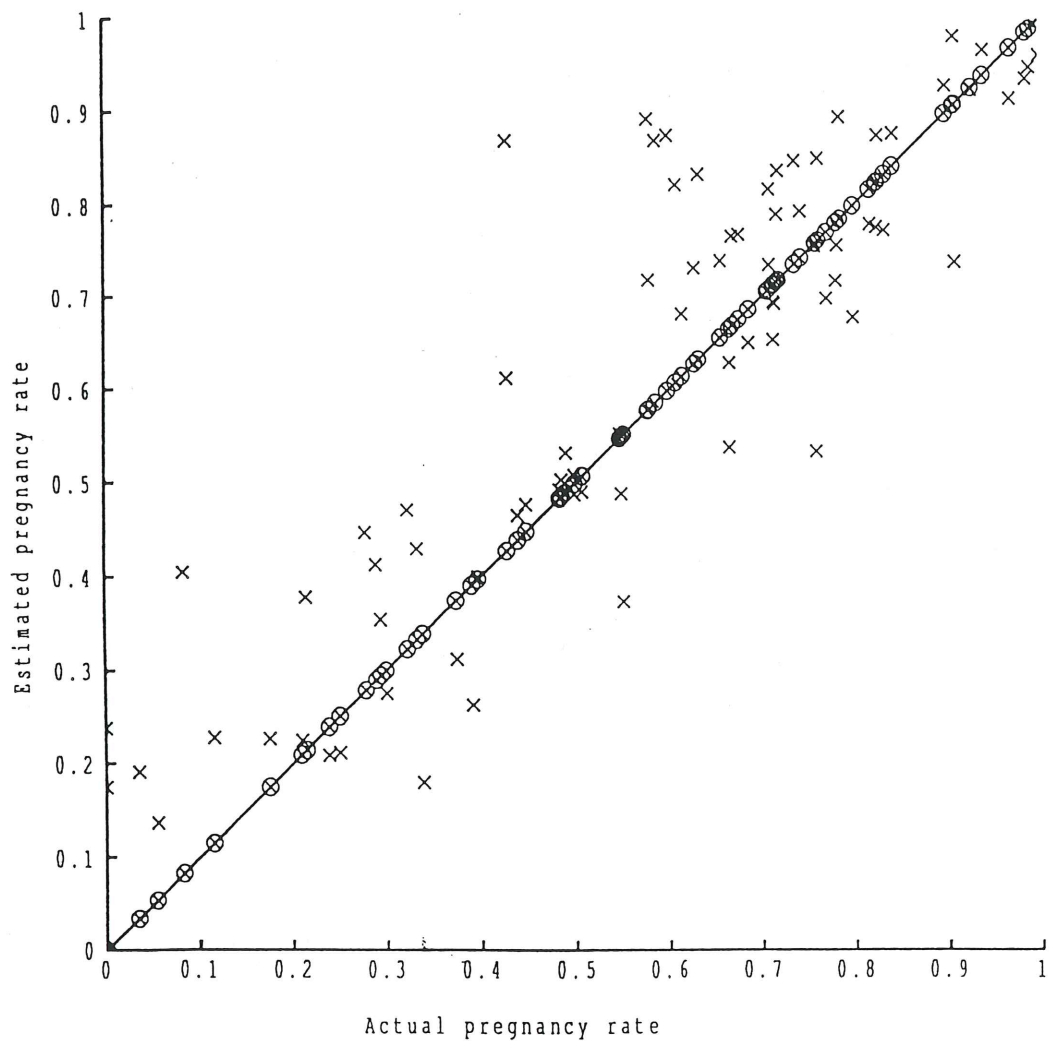


Figure 14. Actual vs estimated pregnancy rates for the Queensland sheep data set, when conception is predicted with the two-stage general linear model (equations 12, 13 and 8).

Northern Australia - cattle

Statistical analysis. The degree of fit from regression analysis of individual predictors is listed in Table 10; R^2 values range up to 70%. As with mortality models, estimated BC was a better predictor than weight, and the lower value for C_{N1} was preferred. The pruned tree-diagram (Figure 15) confirms these relativities, with the first two breaks involving $BC_{0.01}^*$. Further divisions reflect biological effects, and the resultant conception rates are informative.

Table 10. Coefficients of determination (R^2 , as percent) for individual predictors of conception rate (CR , in %/cycle) in the Queensland cattle data set.
Bold entries indicate significant regressions ($P < 0.01$).

FACTORS	Site	Breed	Year Type	Age & Lactation Status
	37.0	20.8	1.7	10.7
WEIGHT VARIATES ³	<i>W</i>	$BC_{0.0157}^*$		$BC_{0.01}^*$
Start of mating	35.1	43.1		48.9
Mid-mating	46.1	56.7		63.2
End of mating	54.4	65.5		69.9
OTHER VARIATES ³	Age (<i>A</i>)	Lactation status (<i>L</i>)		Weight change over mating period (kg/month)
	1.6	10.4		20.0

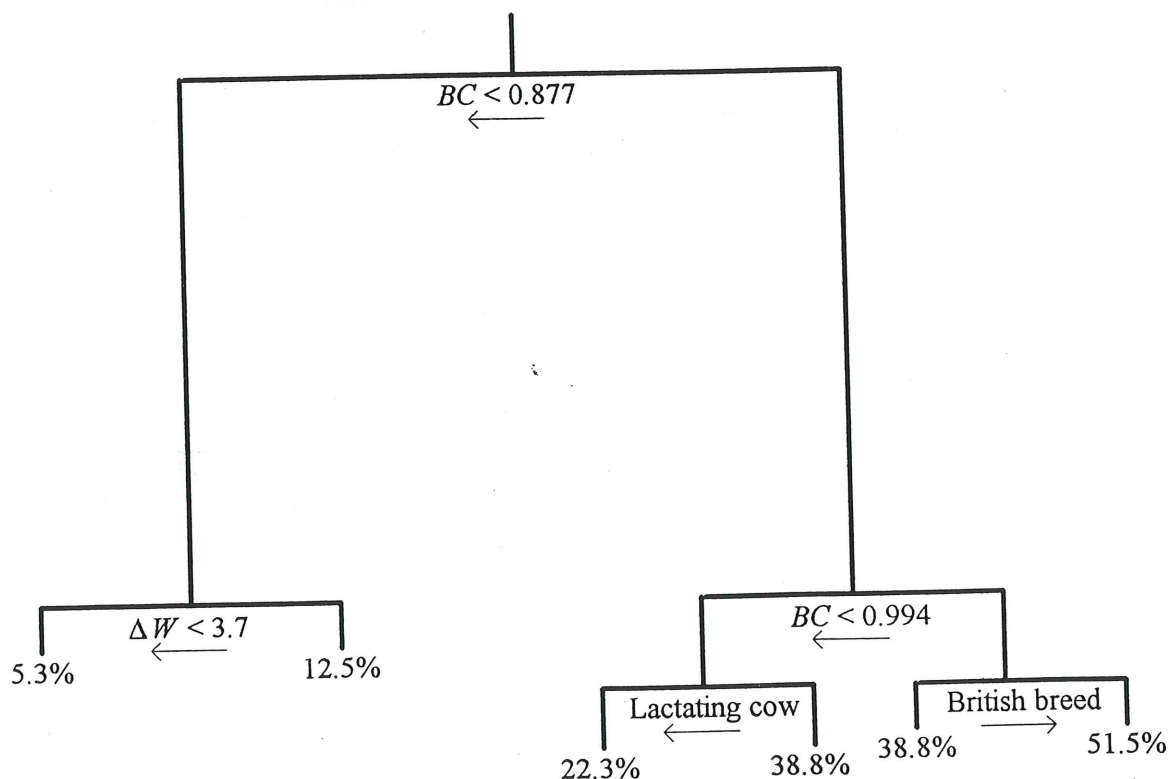


Figure 15. Pruned tree regression diagram for conception rate (CR , per oestrus cycle) in northern Australian cattle.

³ Quadratic models were fitted for all the weight variates.

Although end-of-mating relative weight gave the best fit, mid-mating weight was used as a starting point for the multiple models, because it better reflects average conditions during the mating period. (Multiple models starting with either gave virtually identical fits.) With $BC_{0.01}$ in the model, age/lactation status was the dominant next addition, followed by breed (Table 11). After these terms, quadratic or asymptotic models of weight gain added about the same degree of explanation. Site would have made a similar contribution, but it was excluded from consideration due to problems of extending any model incorporating it and its low contribution (inclusion of site increased R^2 by less than 2%). Again, all interaction models were screened; the $BC_{0.01}$ by weight gain interaction was significant ($P < 0.01$), but was not included in the final model as it increased R^2 by only 0.8%. The adopted model (as illustrated for the continuous variates in Figure 16) is:

$$CR = -1.35 + 2.57BC - 0.99BC^2 + AL + B + 0.0428 \ln(\Delta W + 8.0) \quad (14)$$

where ΔW is weight change during the mating period (in kg per month) and the age/lactation (AL) and breed (B) factors are given in Table 12.

Table 11. Step-forward multiple models predicting conception rate (CR) for the Queensland cattle data set. Bold entries indicate statistical significance ($P < 0.01$).

Terms	F-value (improvement)	R^2 (%)	Std. Error of Estimate (calves/cow)
$BC_{0.01}^*$, Age & lactation status	28.7	72.7	0.043
$BC_{0.01}^*$, Age & lactation status, Breed	5.2	74.9	0.041
$BC_{0.01}^*$, Age & lactation status, Breed, ΔW	15.1	76.4	0.040
$BC_{0.01}^*$, Age & lactation status, Breed, $(\Delta W)^2$	19.6	78.1	0.039
$BC_{0.01}^*$, Age & lactation status, Breed, $(\Delta W)^2$, Site	4.3	79.3	0.038
$BC_{0.01}^*$, Age & lactation status, Breed, $\ln(\Delta W + 8)$	32.6	77.9	0.039
$BC_{0.01}^*$, Age & lactation status, $\ln(\Delta W + 8)$, Site	7.0	79.6	0.038

Table 12. Age/lactation and breed parameters for equation (14).

Age & lactation status	AL	Breed	B
Heifers	0.0	British (F_n)	0.0
Cows (three years old, lactating)	-0.103	European crosses (F_1, F_n)	-0.006
Cows (> three years old, lactating)	-0.046	Africander crosses (F_n)	0.120
Cows (non-lactating)	0.030	Zebu crosses (F_1)	0.061
		Zebu crosses (F_n)	0.025

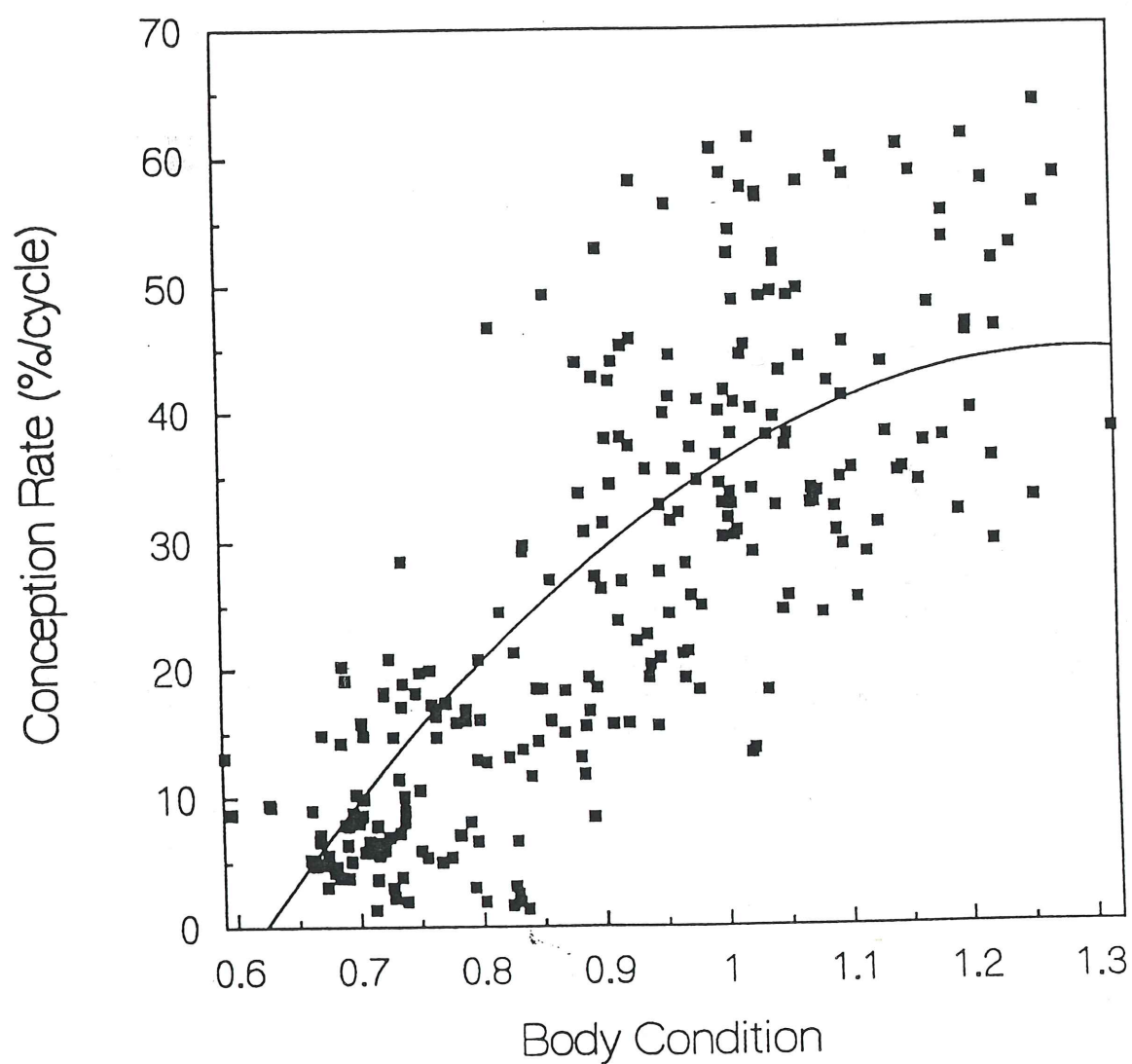


Figure 16. Conception rate in the Queensland cattle data set: fitted relationship between *CR* and body condition (equation 14), and data (adjusted for other terms in the general linear model).

GRAZPLAN equation. The nominated coefficients for the GRAZPLAN conception rate model produced an inadequate fit, so the equation was re-parameterized to fit the data using non-linear regression in GENSTAT.

Fitting the two coefficients representing the slope and position of the sigmoid gave inferior fits (R^2 of 41% to 49%, depending on how many breed-specific constants were fitted). From the statistical analyses, though, it appeared that an upper asymptote of 100% (as assumed by equation 4) was unrealistic for these animals. Fitting an asymptote in the non-linear regression model raised the R^2 from 41% to 47%, which was still inferior to the simple statistical models.

Equation (4) allocates equal weighting to body condition (BC , as estimated by W/N) and relative size (Z , which is N/SRW). A statistical investigation of the effect of Z (not presented here) showed this term to make little practical contribution, either in the linear or multiple models. It was thus hypothesised that BC by itself might be a better independent variate for the sigmoidal relationship, and this proved to be the case; mid-mating-period weights were used (following the statistical results), and a simple sigmoid gave R^2 values of 57% (for $BC_{0.0157}^*$) and 64% (for $BC_{0.01}^*$). Once again, the latter appeared more appropriate to the data, and was adopted as the starting point for model investigations.

After adjusting for BC , the previous analysis identified the effects of "age/lactation" and breed as the most pronounced. These were fitted in the sigmoid by allowing each of the three constants to take a different value for each level of the factor, which did cause some estimation problems in GENSTAT. Inclusion of breed constants, whilst statistically significant, only lifted R^2 by 2.3%. Inclusion of age/lactation status, on the other hand, improved R^2 by 16% to 80% (for a 12-parameter model). Each constant was then reviewed and those with t -values less than 1.5 were pooled, giving a 9-parameter model which also had an R^2 of 80%.

Breed differences were then re-estimated by allowing each breed to increment these fitted constants, with significant improvements retained. Two such improvements were found, separating Africanders and F_1 Zebus from the other pooled breeds. All constants were again screened.

Finally weight change, which appeared as a significant term in the statistical analyses, was trialed as a linear variate to each of the 3 "base" constants. Overall, this change was significant ($p < 0.05$), but R^2 only improved by 0.6 % and none of the individual terms were significant, so this effect was omitted.

Thus, generalisation of the sigmoid function arrived at a 10-parameter model with an R^2 of 82% and a standard error of estimate (s.e.e.) of 0.033. While the number of parameters and the R^2 figure are very similar to those from the statistical model, the s.e.e. is lower; this is primarily because of the higher number of observations which could be fitted to the sigmoid model (weight change was missing for 27 observations in the statistical fits). The final sigmoidal relationship is -

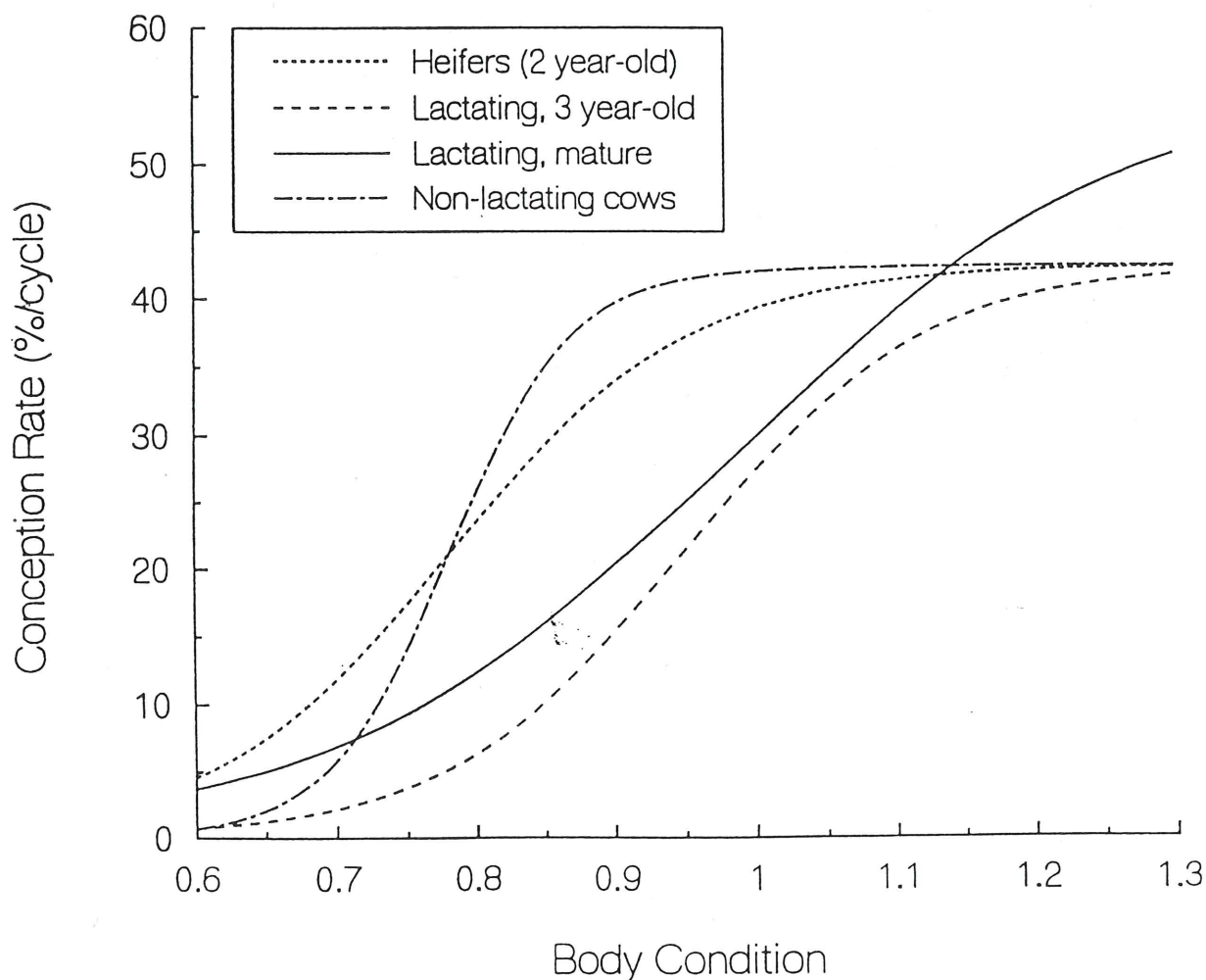
$$CR = \frac{a + a_B}{1 + \exp\left(-b\left(BC_{0.01}^* - (c + c_B)\right)\right)} \quad (15)$$

where the parameters a , a_B , b , c and c_B are given in Table 13.

Figure 17 shows the fitted effect of age and lactation status for the majority of the breeds (British, European and F_n Zebus). Breed differences are indicated in Figure 18, which uses the non-lactating mature cow class for illustration.

Table 13. Parameters for equation (14).

	a	b	c
Heifers	0.423	11.7	0.781
Cows (three years old, lactating)	0.423	11.7	0.948
Cows (> three years old, lactating)	0.562	7.0	0.982
Cows (non-lactating)	0.423	22.6	0.781
	a_R		c_R
Africander crosses (F_n)	0.118		0.0
Zebu crosses (F_1)	0.0		-0.051
Other breeds	0.0		0.0


Figure 17. Fitted effects in the generalised GRAZPLAN equation of age and lactation status on conception rate, illustrated for British, European and F_n Zebu breeds.

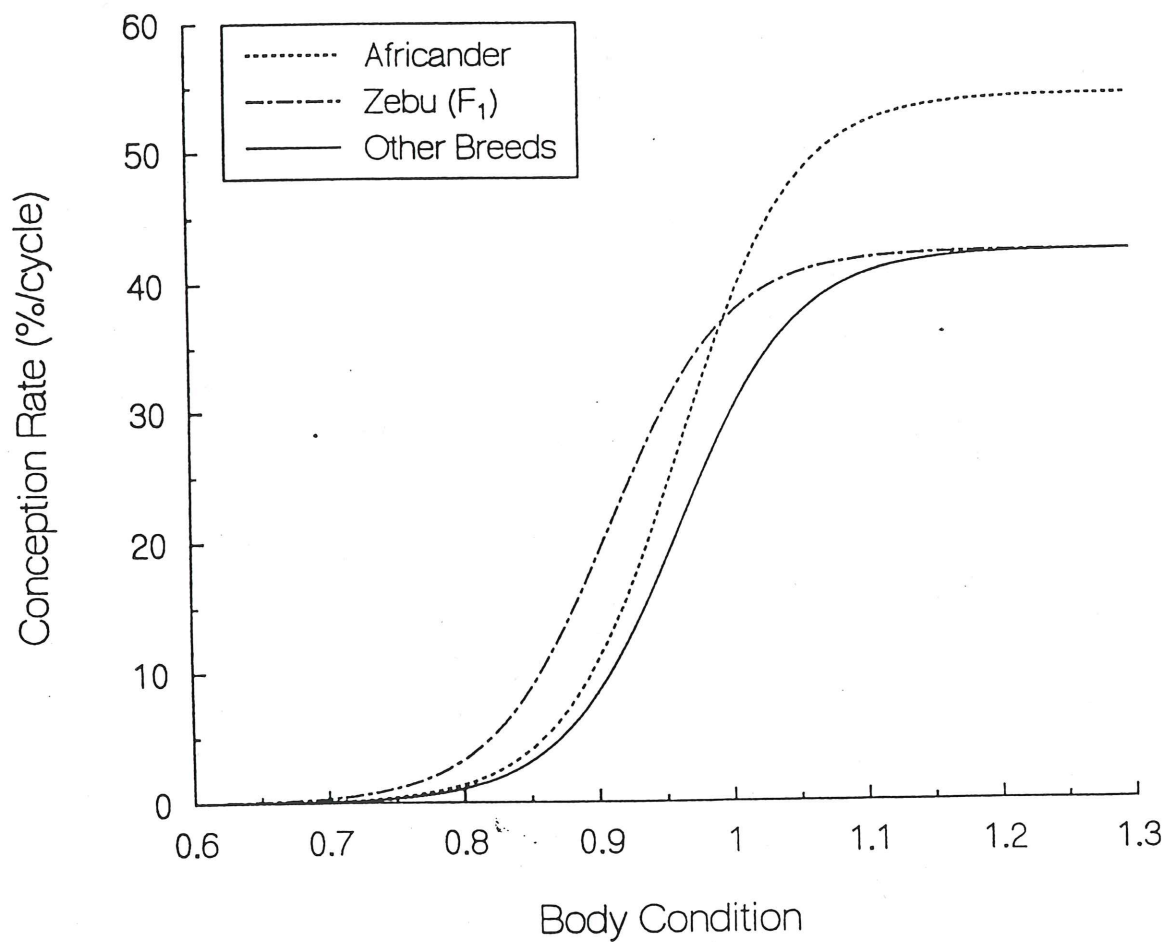


Figure 18. Queensland cattle data set: fitted effects in the generalized GRAZPLAN equation of breeds on conception rate, illustrated for non-lactating mature cows.

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