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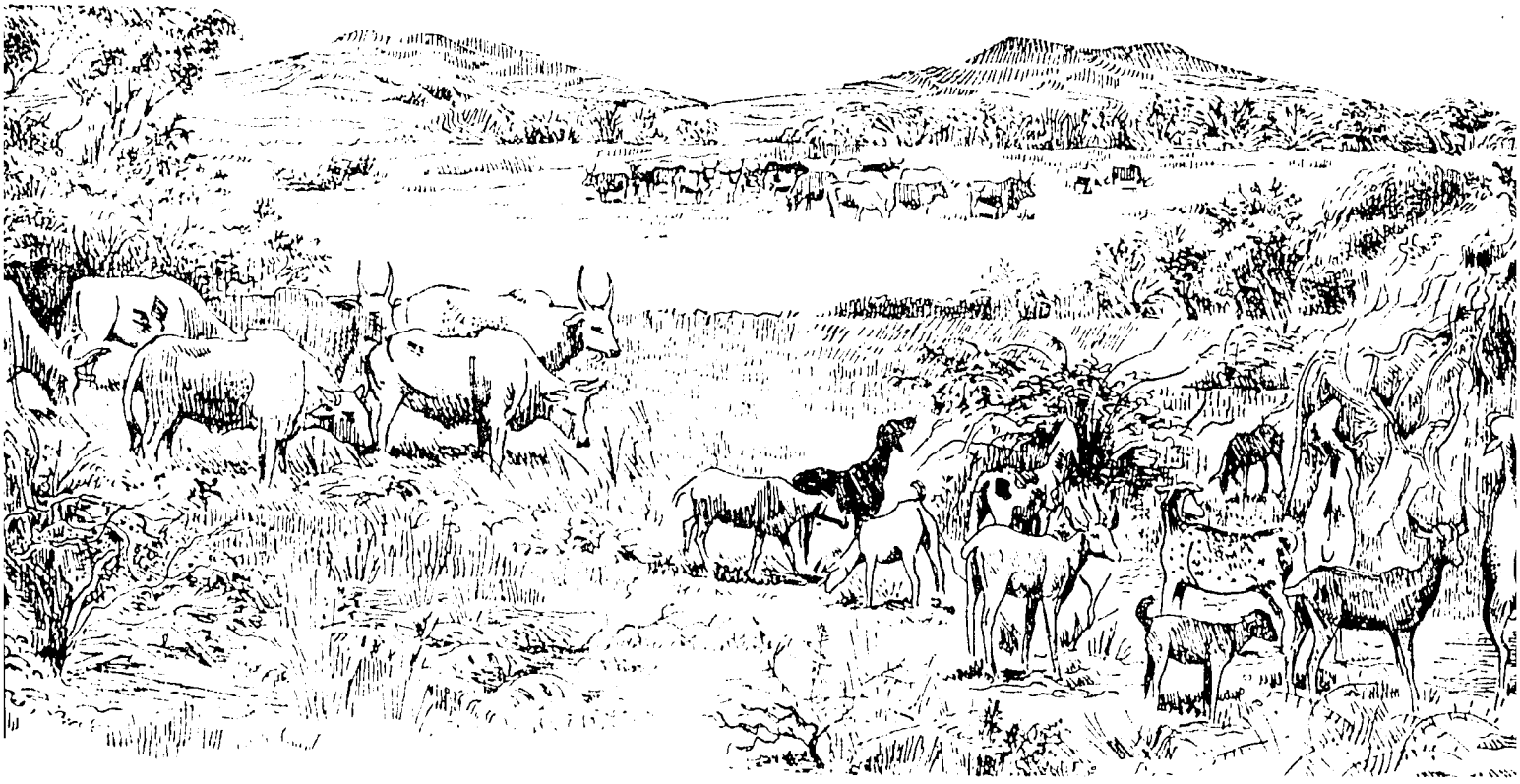

Impacts of milk pricing policy in Zimbabwe

Use of tritiated water in livestock research

Molybdenum in soil–plant–animal systems in sub-Saharan Africa

Pastoral dairying in Africa: Some research and development implications

Fodder banks and labour requirement for cropping

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The *ILCA Bulletin* is a quarterly publication of the International Livestock Centre for Africa. Contributions to the Bulletin are invited from livestock researchers in Africa whose work is related to that of ILCA. The *ILCA Bulletin* is distributed to more than 3000 researchers, policy makers, donors and extension agents throughout sub-Saharan Africa and elsewhere in the world.

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PREFACE

One of the main concerns at ILCA is to generate the scientific and practical knowledge which would help the people in Africa to increase the productivity of their land and animals. The diversity of research work carried out at ILCA is well illustrated in this issue of the *ILCA Bulletin*, which includes articles on such divergent topics as the impact of milk pricing policy in Zimbabwe, the use of tritiated water in livestock research, the role of molybdenum in soil-plant–livestock systems in sub-Saharan Africa, the development of commercial dairying by pastoralists, and the labour requirements for cropping maize in fodder banks and on fallow land.

Governments seek to influence the pattern of production and consumption of agricultural produce by adopting different food pricing policies. In Zimbabwe, the Government's objective is to attain self-sufficiency in dairy products. Analysis of the milk pricing policy adopted in Zimbabwe to further this objective shows that increases in the producer price will result in short-term increases in milk output, while depressing consumer prices for milk has stimulated demand for whole milk; this is increasingly being satisfied by importing dairy products to supplement domestic production. Thus the effects of the pricing policy are inconsistent with the Government's original objective.

Research workers in Africa are often constrained by the lack of suitable guidelines on the use of modern research techniques, partly because such information is usually found only in highly specialised journals. The application of tritiated water in estimating total body water, body composition, water turnover, and milk and feed intake, is one technique for which more information is needed. This need is addressed in the second paper of this issue, which presents a review of the theoretical aspects and potential errors of the method and gives a comprehensive methodology for its use.

Molybdenum deficiency in soils and plants can reduce plant growth and thus crop yields, while high levels of molybdenum are toxic to ruminants. Several studies have been made on the economic importance of micronutrients in general, but their role in the soil-plant-animal systems of sub-Saharan Africa has not yet been examined systematically. ILCA's Soils and Plant Nutrition Section intends to produce a series of reviews on this topic, and the article on molybdenum is the first of them.

Milk versus meat production by pastoralists is an issue featuring high on the agenda of the development debate. Using experience gained while working among pastoralists in several African countries, as well as that of many prominent scientists studying pastoral economies, the author of the fourth article in this issue adds her voice to those contending that pastoral dairying is a far more realistic proposition than meat production, under the prevailing conditions in African pastoral systems.

The last paper examines labour requirements for cropping in fodder banks and on fallow land. The study shows that, while harvesting crops in fodder banks requires more labour, soils inside fodder banks are easier to ridge and produce higher crop yields. The authors conclude that inclusion of a legume interphase in the cropping system can increase farmers' incomes substantially.

Finally, this issue also carries a style guide for authors wishing to publish in the *ILCA Bulletin*. We hope that it will encourage researchers and development agents working in Africa to contribute to the *ILCA Bulletin*, and thus help the Centre in its task of disseminating information on agricultural development in Africa.

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The impacts of the milk pricing policy in Zimbabwe

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SUMMARY

THE MAIN PURPOSE *of this paper is to analyse the effects of government price policies on the production and consumption of milk in Zimbabwe. It begins with an overview of the Dairy Marketing Board (DMB) which is responsible for the collection and distribution of commercial milk products at prices set by the Government. A description of the trends in milk output and the response of commercial milk supply to prices is followed by time-series analysis of monthly milk intake by the DMB. The implications of changes in the milk producer price for the opportunity costs of land and animal draught power in the communal areas are discussed. Finally, the trends in the consumption of dairy products and aggregate demand relationships for whole milk and milk products in Zimbabwe are described.*

INTRODUCTION

Dairy products are one of the strategic commodities in the economy of Zimbabwe, since they are not only a major consumer item but also a main source of farm income and employment in various parts of the country. In line with the Government's objective to attain a level of self-sufficiency in dairy products (Ministry of Agriculture, 1985), several public intervention schemes influencing the pattern of consumption and production of dairy products have been adopted.

One of the market interventions is price control at the producer and retail levels. Government participation in the adjustment of the market price of dairy products imposes certain biases on the distribution of economic benefits between the producers and consumers. For example, if the domestic milk producer price is set above the free trade milk price (e.g. the export price of New Zealand), then the Government is implicitly subsidising the domestic producer while explicitly providing signals to the other economic sectors to channel resources to the dairy industry. On the other hand, if the domestic retail price of milk is set below the equivalent free trade price, consumption of milk is being encouraged in excess of the level dictated by the free market. The magnitude of producers' and consumers' response to prices will determine the corresponding cost of the government intervention policy, which can sometimes be high. In order to evaluate the dairy price policy of Zimbabwe, this paper attempts to provide an empirical estimate of the response of both the consumers and producers to milk price adjustments. Furthermore, since the prices of dairy products can affect the value of inputs and outputs, the paper examines the theoretical aspects of dairy input-output adjustments made by subsistence farmers who, because of inadequate marketing structures, are usually unable to reap the full benefits of government price policies for dairy products.

THE DAIRY MARKETING BOARD: ITS ROLE IN THE PRICE POLICY

The dairy sector in Zimbabwe is composed of three classes of producers:

- Large-scale commercial dairy producers with an average herd size of 90 purebred animals (mostly Friesians and Jerseys) in prime farming areas with annual rainfall ranging from 750 to 1000 mm.
- Small-scale commercial dairy producers with an average herd size of six animals (which can be purebred, crossbred or indigenous). The marketable surplus of these producers is limited to local retail sales, and they operate in a range of environments (e.g. with annual rainfall ranging from 450 to 1000 mm).
- Communal dairy farmers owning indigenous beef cattle. There are about 700 000 communal farms in Zimbabwe, most of them in areas with average annual rainfall of less than 400 mm.

Prior to 1912, large-scale commercial milk distribution was effected directly from farmers to consumers. An increase in commercial milk production led to the establishment of small creameries between 1912 and 1930. As milk production increased further, the small creameries were unable to distribute the milk efficiently and were in turn replaced by producer cooperatives. These not only distributed milk but also converted it into final dairy products to be sold in the urban centres of Zimbabwe. Further increases in milk production led to the establishment of the Milk Committee in 1949. Its main function was the resale of milk to existing dairies. On 1 October 1952, the Committee was replaced by the Dairy Marketing Board whose main functions are:

- To purchase, collect and receive milk and butterfat from registered producers at prescribed prices.
- To process, manufacture and distribute milk and milk products at prescribed prices.

The determination of milk producer prices is oriented towards the concept of financial viability. In Zimbabwe, a cost-of-production model of commercial farms is used to determine initial producer price levels. These prices are revised by the Cabinet after considering such other factors as the state of the trading account of the DMB, the export prices of milk products and the target levels of milk output.

The setting of milk consumer prices (initiated by the Ministry of Trade and Commerce) seems to be largely dependent on the type of milk products the Government wishes to subsidise. For example, prior to 1975, the Government supported a policy which allowed the DMB to sell some milk products at less than their actual accounting cost. The deficit was supposedly offset by sales of fresh milk. However, as a result of selling milk products below average costs, the DMB financial deficits have increased (Table 1).

The deficits are financed by government loans. Jansen (1982) argued that the DMB trading deficit is a consumer subsidy. She arrived at this conclusion by comparing domestic retail prices with their equivalent border prices and found that the actual retail price of milk in Zimbabwe is only 41% of its border price.

During its initial years of operation, the DMB absorbed the Dairymen's Cooperative Limited (Harare), Gatooma Cooperative Society, Rhodesian Cooperative Creameries and the Bulawayo Creamery. In 1962 and 1963 the DMB also operated dairies in Zambia. A recent addition to the DMB creameries is the Chipinge Milk Plant, formally opened in 1983. A more recent activity of the DMB is to encourage dairying in suitable communal areas through the Small Farm and Peasant Development Programme, the objective of which is to effect a more equitable distribution of agricultural incomes.

Table 1. *Trading account deficits of the DMB by fiscal years.*

Fiscal year[a]	Deficit[b] ('000 Z$)
1978/79	3 700
1979/80	2 108
1980/81	10 100
1981/82	18 300
1982/83	35 658
1983/84	38 651
1984/85	28 000[c]

[a] Fiscal year is from 1 July to 30 June.

[b] The deficit is estimated as total sales minus the sum of total sales cost, overhead expenses, general management expenses and net operating expenses.

[c] Estimate.

Source: DMB (1984).

THE STRUCTURE OF DOMESTIC MILK OUTPUT

All milk sold in urban areas is produced by the commercial farms. Milk produced in the communal areas is consumed locally. Given an average yield of 2 litres per cow per day (over a milking period of 4 to 6 months), annual milk production will be close to 15 million litres (DMB, 1984). The aggregate trends in milk output from large-scale commercial dairy producers are given in Table 2.

The milk production data in Table 2 imply that the annual growth rate for commercial output was 2.28%, for milk yields 2.49% and for cow numbers −0.20%. These rates were estimated using semi-log (base e) regression relationships; the growth rate for cow numbers was not statistically significant.

As a proportion of the total national dairy herd, the number of cows in milk has changed very little (by about 0.7% per year over the 1959–1984 period). According to CSO (1984) statistics, in 1959 cows in milk represented 36% of the total dairy herd (105 800 head) whereas in 1984 they accounted for 42% of the dairy herd (104 500 head). The number of cows in milk is affected to a certain extent by the efficiency of labour relative to fixed capital inputs. In Zimbabwe there are heavy pressures to increase the minimum wage. If the wage push persists, commercial farmers will shift to more intensive use of capital inputs provided that foreign exchange is available for their importation. The use of more fixed capital will result in a larger inventory of cows in milk. This trend was observed in the country by Higgins (1972) who noted that the number of cows per herd increased as the milking system became more mechanised.

Prices of milk, beef, corn and technology influence milk output. The impacts of such

Table 2. *Milk output[a] from large-scale commercial dairy producers, 1965/66 to 1983/84.*

Year	Commercial milk output (million litres)	Number of cows in milk (thousand head)	Milk yield per annum (litres)
1965/66	101.6	41.5	2 448
1966/67	106.9	40.7	2 627
1967/68	118.5	43.3	2 737
1968/69	127.0	47.0	2 702
1969/70	129.0	47.6	2 710
1970/71	134.6	48.0	2 804
1971/72	141.7	48.4	2 928
1972/73	155.2	50.9	3 049
1973/74	155.3	49.7	3 125
1974/75	142.5	48.3	2 950
1975/76	148.8	49.4	3 012
1976/77	155.9	49.5	3 149
1977/78	151.0	48.1	3 139
1978/79	145.2	43.9	3 308
1979/80	154.9	42.9	3 611
1980/81	149.1	42.5	3 508
1981/82	150.5	40.7	3 698
1982/83	172.5	42.5	4 059
1983/84	181.1	43.8	4 135

[a] On-farm consumption of milk is excluded from milk output.

Source: CSO (1984).

factors were examined in this study using the following equations (fitted for the period 1965 to 1984)[1]:

$$\log Ym = 7.237 + 0.384 \log Pm - 0.050 \log Pc - 0.056 \log Ra + 0.126 \log t \quad (1)$$

(0.150) (0.102) (0.047) (0.018)

$R^2 = 0.91$ DW = 1.78

$$\log C = -0.3721 + 0.1089 \log Pb + 0.2496 \log BPm - 0.1770 \log BPc + 0.9156 \log BC - 0.0400 \log t \quad (2)$$

(0.1327) (0.1081) (0.0492) (0.1432) (0.0159)

$R^2 = 0.95$ H = −1.56

where:

Ym = annual milk yield (kg),

C = number of cows in milk (thousand head),

B = lag operator (for example BC means the number of cows during the previous period),

Pm = producers' milk price per kg deflated by the cost of living index (Z$),

Pc = price of corn per kg deflated by the cost of living index (Z$),

Pb = price of beef per kg deflated by the cost of living index (Z$),

t = time variable,

Ra = national average annual rainfall (mm),

DW = the Durbin-Watson index, and

H = the h-statistic proposed by Durbin as an alternative test for autocorrelation. The estimated H is equal to the first-order serial correlation parameter multiplied by the constant SQ [n/(1-nv(a))],

where:

SQ = the square root operation,

n = sample size, and

v(a) = the variance of the coefficient of the lagged variable.

All logarithmic transformations are to the base e.

All R^2 have been adjusted for degrees of freedom.

Numbers in parentheses are standard errors of the respective regression coefficients.

The coefficients for log Pm and log BPm in equations 1 and 2 are statistically significant at the 5% level. The short-term milk price elasticity (derived as the sum of the coefficients of log Pm and log BPm) is 0.63, which means that a 10% rise in the milk price will induce an increase of 6.3% in milk output. About 61% of the total change in output arising from a milk price change can be attributed to milk yield response. The technological potential for milk yield increases on commercial farms is yet to be fully exploited. Data obtained through the milk recording scheme of the Department of Research and Specialist Services for 1984 indicated that Friesians can produce 9435 to 13 629 kg of milk per cow per annum compared with 5456 to 7303 kg for the Jersey breed.

The estimate of the milk yield response to milk price changes in Zimbabwe is lower than those obtained for developed countries. In Great Britain, for example, the response was estimated to be 0.50 to 0.54 (Buckwell, 1984). The estimated, long-term milk price elasticity for Zimbabwe is 2.96 – derived from equation 2 as (0.2496/(1−0.9156)) –, which is similar to that obtained by Chen et al (1972) for the USA.

It is usually also argued that as the price of beef increases, a corresponding rise in the capital value of cattle occurs. Hence, in the short run, there will be a tendency for the dairy cow herd inventory to increase to take advantage of capital gains arising from an increased beef price. The positive sign of the coefficient of log Pb in equation 2 tends to support such a directional hypothesis.

In both equations 1 and 2, the absolute magnitude of the milk price elasticity is greater than that for the price of corn. Chavas (1982) argued that commodity price elasticities for supply relationships are greater than the corresponding input price elasticities due to the existence of more options for input substitution in the production set. The statistical significance of the corn price (in logs) coefficient is more prominent in equation 2 than in equation 1. This means that through their effects on culling policies, changes in the price of corn will influence the size of the dairy cow herd more than the annual yield per cow. Since adjustments in the dairy cow herd require a longer biological process than changes in annual cow productivity, shifts in corn prices have a longer-lasting impact on milk output.

[1] All the basic data inputs used in estimating the regression relationships in this paper were obtained from the Dairy Marketing Board, the Central Statistical Office and the Agricultural Marketing Authority of Zimbabwe.

TIME-SERIES ANALYSIS OF COMMERCIAL MILK OUTPUT

The seasonality of commercial milk output in Zimbabwe was analysed using the monthly milk intake data of the DMB for Harare, Bulawayo, Gweru, Kadoma and Mutare (which includes Chipinge) for the period 1975/76 to 1983/84. In 1983/84 these areas accounted for 52%, 12%, 21%, 8% and 7% respectively of the national milk intake of the DMB.

Autocorrelation functions were plotted for the five areas (Figure 1). The autocorrelation coefficient is estimated between monthly milk intake data (say Ot and Ot-k) which are separated by k intervals of time. A common feature manifested in the autocorrelation functions is the presence of spikes at lags 12, 24 and 36, which confirms the presence of an annual seasonal pattern. Another feature is a declining trend in the coefficients after each spike.

The seasonality of DMB milk deliveries is partly influenced by the seasonal prices applied by the Government during a year and partly by the availability of feed supplies. For example during the fiscal year of 1983/84, the seasonal producer price was highest (at Z$ 0.32/kg milk) in November. The peak period of the annual rainy season is normally from November to January, and since feed production is positively correlated with rainfall levels, feed supplies during that period will be adequate to meet the dairy farmers' demand for feed at favourable prices.

If adequate monthly time-series are available, seasonal causal relationships between prices and monthly milk deliveries can be examined using regression functions. As this was the case, the DMB monthly milk deliveries for the period 1975/76 to 1983/84 were analysed using the following fitted autoregressive models:

$$(1-0.9512\,B)\,(1-B(12))\,Oh = ah \quad Q = 9.77 \quad (3)$$
(−1.5300)

$$(1-0.8911\,B)\,(1-B(12))\,Ob = ab \quad Q = 8.14 \quad (4)$$
(−2.4700)

$$(1-0.9175\,B)\,(1-B(12))\,Og = ag \quad Q = 5.64 \quad (5)$$
(−2.2200)

$$(1-0.8853\,B)\,(1-B(12))\,Ok = ak \quad Q = 11.93 \quad (6)$$
(−2.5300)

$$(1-0.9887\,B)\,(1-B(12))\,Om = am \quad Q = 6.53 \quad (7)$$
(−3.4200)

where:

B(12) = the lag operator applicable to a

12-period lag (e.g. the DMB milk intake during the same month, one year previously),

O = monthly milk intake,

a = the error term,

h, b, g, k and m refer to Harare, Bulawayo, Gweru, Kadoma and Mutare, and

Q = the sum of squares of the autocorrelation coefficients multiplied by the number of degrees of freedom.

The numbers in parentheses are the t values of the coefficient. Note that the null hypothesis is that the coefficient equals one. The portmanteau test, which involves estimating Q, indicates that the models adequately fit the data i.e. the estimated Q is less than the critical chi-square value (36.42).

The estimate of total milk delivery provides an implicit index of the pressures on milk producer price adjustments while the regional monthly forecasts indicate the growing demand imposed on the regional DMB distribution facilities. Table 3 gives estimates of monthly milk intakes by the DMB from the five areas in 1985/86. Total milk intake for 1985/86 was estimated to be 191 692 700 litres, an increase of 2% over the 1984/85 intake of 187 987 980 litres. This implies an upward pressure in the real milk producer price of 1.26%.

Table 3. *Estimated monthly milk intakes from the Harare, Bulawayo, Gweru, Kadoma and Mutare areas, July 1985–June 1986.*

	Milk intake ('000 litres)				
Month	Harare	Bulawayo	Gweru	Kadoma	Mutare
July	8 111.19	1 693.90	3 027.56	1 151.04	1 175.38
August	8 311.45	1 753.17	3 091.52	1 159.25	1 212.23
Sept	8 171.77	1 711.74	3 096.25	1 144.86	1 221.34
Oct	8 626.46	1 819.16	3 333.58	1 184.15	1 371.58
Nov	8 663.32	1 821.58	3 427.27	1 137.02	1 362.93
Dec	9 585.58	2 006.68	3 812.02	1 273.26	1 438.50
Jan	9 530.61	1 870.31	3 866.95	1 396.67	1 384.85
Feb	8 141.33	1 621.76	3 232.86	1 165.64	1 124.72
March	8 652.71	1 682.58	3 371.32	1 237.12	1 153.24
April	8 243.32	1 568.70	3 126.79	1 172.27	1 089.14
May	8 305.97	1 625.89	3 208.63	1 155.10	1 128.62
June	7 965.48	1 556.79	2 991.42	1 125.69	1 100.82
Total	102 309.19	20 732.26	39 586.17	14 301.67	14 763.41

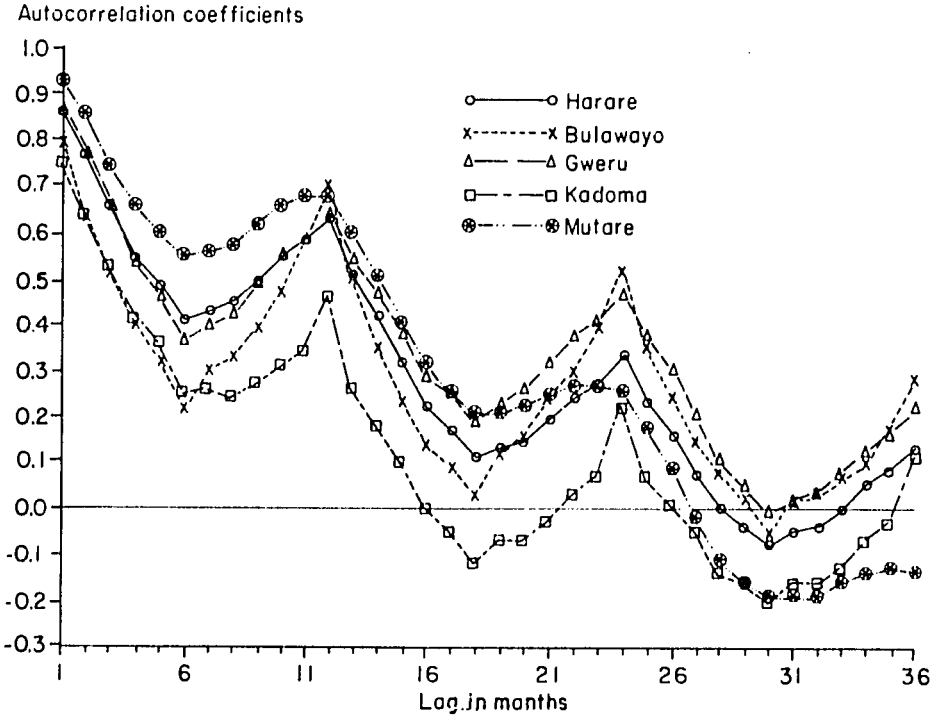
THE COMMUNAL SECTOR AND MILK PRICE CHANGES

Information on dairying in communal areas is scarce. A recent case study undertaken by the Dairy Marketing Board (1984) at Chikwaka provides some insights into the nature of milk production in such areas. In 1984, the average milk production on the 310 communal farms surveyed was 2 kg/cow/day over lactations of 4 to 6 months, compared with 13.36 kg/cow/day on commercial farms. The DMB estimates that production of 3 to 4 kg milk/cow/day can be achieved through improved nutrition.

Milk price policies affect communal farmers differently than the commercial farmers. On communal farms, livestock play a multi-purpose role, providing draught power and manure in addition to such commodities as beef and milk. As a result, a change in the price of milk will have repercussions on the costs of other farm activities.

Consider the case where a cow is used to plough land and is also a source of milk to the farm household. The increase in the milk price can lower the cost of the animal's draught power services and can increase land costs. The larger return from dairy activities, arising from a higher milk price, will induce an expansion of the cow herd (since milk yield per cow is low). Concomitant with such a change is an increase in the supply of male calves which may not be fit for beef production. However, as there is a constant demand for draught power, the male calves can be used as a labour input to crops at a lower cost. The lower animal labour cost can induce more extensive cropping. With low crop yields, crop output can only be increased by increasing the acreage planted. The increased demand for land (given a fixed supply) will

Figure 1. *Autocorrelation patterns of milk intake for Harare, Bulawayo, Gweru, Kadoma and Mutare.*



increase the opportunity cost of land. As a consequence, persons enjoying favourable land-use rights will reap economic rents.

MILK CONSUMPTION

A substantial portion of milk products is consumed in the form of whole milk. For example, of the 181 million litres of milk utilised by the DMB in 1983/84, 59% was sold as whole milk. Over the period 1966/67 to 1983/84, DMB sales of whole milk increased from 7.35 to 13.27 kg per caput, showing an annual growth of 3.3%. Data from the DMB indicate that major portion of this growth was accounted for by increased consumption in high-density urban areas, where the DMB whole milk sales increased from 0.1 million kg in 1954 to 17.7 million kg in 1975. Prior to the 1964–1968 period, whole milk consumption in these areas was suppressed due to the absence of a milk delivery system.

An aggregate demand relationship for whole milk was estimated using CSO (1984) data for the 1965–1983 period in the following equation:

$$\log Dt = 4.209 - \underset{(0.127)}{0.658} \log Pmr + \underset{(0.19)}{0.124} \log t + \underset{(0.101)}{0.086} \log Ppr \qquad (9)$$

$$R^2 = 0.94 \quad DW = 1.83$$

where:

Dt = per caput consumption of whole milk (kg),
Pmr = retail price of whole milk deflated by the cost of living index (Z$/kg), and
Ppr = retail price of powder milk deflated by the cost of living index (Z$/kg).

All the coefficients have the correct signs. Except for the coefficient of log Ppr, the rest are statistically significant.

The consumer whole milk demand relationship highlights the pressure exerted by the Government on the price of fresh milk. For example, a 10% decline in the real price of fresh milk will induce a 6.58% increase in per caput consumption of whole milk. In the absence of sufficient growth in domestic milk production to satisfy the increased demand for whole milk, shortfalls have to be met by importing dairy products. The total value of dairy imports to Zimbabwe rose from Z$ 145 000 in 1978 to Z$ 2 648 000 in 1983, the majority of the imports being in the form of skimmed milk.

Aggregate demand relationships were also estimated for other major dairy products such as lacto (acidulated milk). Although the resulting fits were quite poor and the standard errors of the regression coefficients were large, the own-price elasticity for lacto (–0.595) was consistent with previous estimates (e.g. –0.65 obtained by Ruigu (1979) using the data of the Kenya Creameries Cooperative for the 1962–1975 period). The elasticity parameter indicates that a 10% drop in the real price of lacto will increase per caput consumption by 5.95%.

Lacto products are usually consumed more in the high-density urban areas. For example, DMB records showed that sales of lacto to such areas increased from 1.13 million gallons in 1966 to 2.2 million gallons in 1969. Hence, if the Government wishes to increase lacto consumption to improve the nutritional status of low-income urban families, then the subsidy of the lacto retail price must be increased.

The absolute magnitude of the milk demand price elasticity plays a role in determining the 'appropriate' prices for milk products, since the trading deficit of the DMB is considered as one of the crucial variables in the milk pricing process. If the Government maximises social welfare (defined as a function where milk prices and consumers' income are independent variables) subject to a zero profit condition for DMB, then the price deviation of, say, consumer whole milk from the marginal cost of producing it should be set equal to (Varian, 1984):

$$k/Ei = (Pm - MCm)/Pm \qquad (10)$$

where:

Pm = unit price of whole milk,
MCm = marginal cost of producing whole milk,
Ei = own-price elasticity for whole milk, and
k = a constant whose value depends on the shadow price corresponding to the zero profit constraint and the marginal utility of income.

If the premium attached by the DMB in meeting a zero profit goal is equal to the utility value attached by domestic milk consumers to their incomes, then, based on the elasticity parameter of equation 9, the whole milk price can be increased by 203% without affecting the consumers' welfare. It is recognised that such a large price adjustment cannot be undertaken abruptly. It should be a goal intended to be accomplished gradually in order to improve the efficiency of the DMB.

CONCLUSIONS

The major findings of the analysis of the effects of the milk price policy in Zimbabwe are:

- The short-term response of commercial milk output to producer price increases will be mainly in the form of yield increases. It is estimated that a 10% rise in the milk producer price will result in a 6.3% increase in milk output.
- The Government's policy of depressing consumer prices for milk is not consistent with the objective of achieving self-sufficiency in dairy products. The low consumer price for milk has encouraged its consumption. Whole milk demand estimates in this paper indicate that a 10% reduction in the retail price of whole milk would increase per caput consumption by 6.58%. The rapid rise in milk consumption has increased the trading deficits of the DMB and has resulted in importations of dairy products.
- The retail price of fresh milk can be increased by as much as 203% without substantially affecting public welfare.
- A change in milk price can affect the opportunity costs of such major inputs as land and animal draught power in the communal areas.

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The use of tritiated water in livestock research in Africa: Theory, application, methodology and potential errors of the technique

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SUMMARY

TRITIUM, *the radioactive isotope of hydrogen has a number of applications in livestock research. Combined with the water molecule, it forms tritiated water (HTO) which can be used to estimate total body water, body composition, water turnover, milk intake and feed intake. Since the application of HTO in livestock research in Africa is likely to become more widespread with the increasing availability of scintillation counters, a review is made of the theoretical aspects of the technique and its potential errors. A comprehensive methodology is also given. The latter is of particular importance given the lack of suitable guidelines for research workers in Africa.*

INTRODUCTION

Tritiated water has been used for animal research for many years but its application in Africa in livestock research has been limited, not least by the scarcity of the sophisticated and expensive equipment needed to measure it. Moreover, much of the data in the literature lack credence because the values are often unvalidated, and insufficient or even no information is given on counting procedure, which can be a major source of error in the method.

Since validation usually requires slaughter, total dissection and a laborious dessication procedure, it is rarely undertaken, so that detailed description of sample counting becomes essential if other workers are to be able to repeat the results. The absence of such information has led to questionable results, even to the extent that tritiated water space is often reported as total body water space, the two being regarded as synonymous. This in part is caused by a reluctance of biologists to study the radiation biology and applied physics which are the basis of the technique, and partly because such information is often to be found only in highly specialised literature.

For those who may wish to consider tritiated water as a tool for livestock research in Africa, a better understanding of the theory behind the technique may lead to greater accuracy and more convincing results. This paper presents a theoretical outline of the technique, highlights its potential errors, and describes a methodology for the use of tritiated water under field conditions.

WHAT IS TRITIATED WATER?

Tritiated water is water which has been labelled with the radioactive isotope of hydrogen, tritium (^3H). This is distinct from water which is labelled with deuterium (^2H), the stable isotope of hydrogen. Tritiated water is variously known as tritium oxide, HTO, TOH or ^3H_2O, while deuterated water is known as heavy water, deuterium oxide, D_2O, ^2HHO, ^2H_2O, HDO or DOH. For the purposes of this article, the abbreviation HTO will be used for tritiated water.

Tritiated water is used in animals because it is cheap and relatively safe. For ethical reasons, deuterium oxide is usually used for humans since deuterium is a stable isotope and exposure to radiation is obviated. Measurement of deuterium is achieved by mass spectrometry.

Being an unstable isotope, tritium decays with the emission of a neutron to a rare isotope of helium (He) as shown in the following equation:

$$^3_1H \rightarrow {}^0_{-1}\beta + {}^3_2He \qquad (1)$$

The emitted β particle has a maximum energy of 18.6 keV and a maximum range in air of 6 mm. The time taken for a given quantity of decaying atoms to reach half their initial activity is known as the radiochemical half-life, and for tritium this is 12.26 to 12.43 years.

The activity of radioactive material is measured in S.I. (Système international) units of the becquerel (Bq) which replaces the curie (Ci). One Bq is equal to one disintegration per second ($d.sec^{-1}$) and one Ci is equal to $3.7 \times 10^{10} d.sec^{-1}$. The Bq is the reciprocal of the Ci and is equivalent to $2.703 \times 10^{-11} sec.d^{-1}$. Since the radioactive material is normally supplied with a 'carrier' of the stable isotope of the same element, the amount of isotope is expressed per unit mass. This is the 'specific activity' which is measured in Bq, Ci or disintegrations per minute per mole (or per gram) of mixture.

In biological experiments, activities used are usually measured in millicuries (mCi), microcuries (μCi) and nanocuries (nCi). However, since such activities are increasingly described in units of gigabecquerels (GBq), megabecquerels (MBq) and kilobecquerels (kBq), both sets of units will be used in this paper.

HTO AS A MARKER

Animals are made up of between 50 and 80% water, and 99% of the molecules in an organism are water molecules (Macfarlane and Howard, 1972). The administration of a known quantity of HTO will allow an estimate of body water volume (HTO space) to be made *in vivo* using the dilution principle. HTO (the tracer) is assumed to mix completely with body water (the tracee), and a sample of body fluid after equilibration of the tracer will allow body water to be estimated following the preparation of standard solutions.

MEASUREMENT OF HTO

Liquid scintillation counting

Radiation can be detected and quantified by two methods: gas ionisation and excitation. Since HTO is a soft β emitter, its measurement using gas ionisation techniques such as the gas-flow counting Geiger-Müller tube is still only about 5% efficient. Instead, HTO can be measured indirectly as a result of the ability of certain compounds to fluoresce in the presence of β particles. This method is known as liquid or internal scintillation counting.

The sample to be counted by liquid scintillation is dissolved in a solvent (usually toluene, xylene, anthracene or cumene) which fluoresces. The light emitted is of such a short wavelength that it is immeasurable, and this necessitates the presence of another compound, the primary fluor, which absorbs the light energy and converts it to light of a longer wavelength. A common primary fluor is PPO (2,5-diphenyloxazole). Fluors are heteroaromatic compounds with several double bonds, one part of which is formed by sigma-electrons constituting a rigid bond while the other part is formed by delocalised pi-electrons which absorb the energy from a β particle and jump to a higher energetic, or excited, state when they release extra energy in the form of photons (Wallac LKB, 1977).

Depending on the photochemistry of the primary fluor, a secondary fluor may be used to reconvert the light into a detectable wavelength. Some primary fluors such as Butyl-BPD (2-(4'-t-butylphenyl)-5-(4''-biphenyl)-1,3,4-oxydiazole) emit light at a detectable wavelength and thus do not need secondary fluors. The commonest secondary fluors are bis-MSB [p-bis-(o-methylstyryl) benzene] and POPOP [1,4-di-(2-(5-phenyloxazolyl)) benzene].

The combination of solvent, primary and secondary fluors is known as the scintillation cocktail. The light emitted is converted into an electric pulse via a photomultiplier tube; the pulse is directly proportional to the energy of the initial radioactive event. The whole process is shown diagrammatically in Figure 1. The efficiency of detection of ^{3}H by liquid scintillation is frequently up to 50% of total disintegrations.

Quenching

The errors that can arise from liquid scintillation counting may be due to the limitations of the scintillation counter or to sample preparation. However, as the manufacturers of modern scintillation counters have eliminated such electronic errors as photomultiplier noise, the major error source is likely to be in the sample preparation and the use of, or failure to use, counting standards.

Interference with the passage of light from the sample to the photomultiplier is known as quenching. Quenching reduces the number of single photon events that are recorded, and it can take three forms:

- Optical quenching, which occurs when the counting vials vary in thickness or are dirty;
- Colour quenching, which occurs when colour in the sample absorbs light prior to its leaving the vial; and
- Chemical quenching, which occurs when some chemical in the sample interferes with the various energy transfer processes in the scintillation cocktail.

Perhaps the major source of error in liquid scintillation counting of biological materials is the assumption that all samples are chemically identical and that it is sufficiently accurate to use relative counting (counts per minute, c.p.m. or ct.min^{-1}). However, as biological materials vary in quench characteristics between animals, between samples (milk, plasma, urine), and at different times, every sample should be converted to absolute counts (disintegrations per minute, d.p.m. or d.min^{-1}) unless the efficiency of counting is known to be identical in all samples. Even if pure water is extracted from the biological material, counting efficiency may vary since water itself is a quenching agent.

When a standard solution is used in body-composition or water-turnover studies, the degree of quenching in the standard must be similar to that of the sample being counted in order to avoid conversion to d.min^{-1}. However, background samples are frequently taken from well-fed animals while labelled samples may come from fasted animals, and this has been the cause of variations in quench in both milk and plasma owing to changes in blood and milk chemistry (Nicholson, unpublished results).

Efficiency determination

The determination of quenching is synonymous with the determination of sample counting efficiency. Reliance on ct.min^{-1} assumes that the efficiency of counting is constant, which in practice it will not be since chemical and optical quenching can vary unpredictably. When biological materials are counted directly there is the added problem of colour quenching.

The three commonest methods of quenching correction are a) the internal standard method, b) the external standard ratio method, and c) the sample channel's ratio method (Kobayashi and Maudsley, 1974; Wallac LKB, 1977).

Internal standard (IS) method. With this method the sample is counted, a known and constant amount of non-quenching radioactive standard is added, and the sample is recounted. The standard will have been counted previously in the absence of quenching agents. The counting efficiency coefficient is then calculated as:

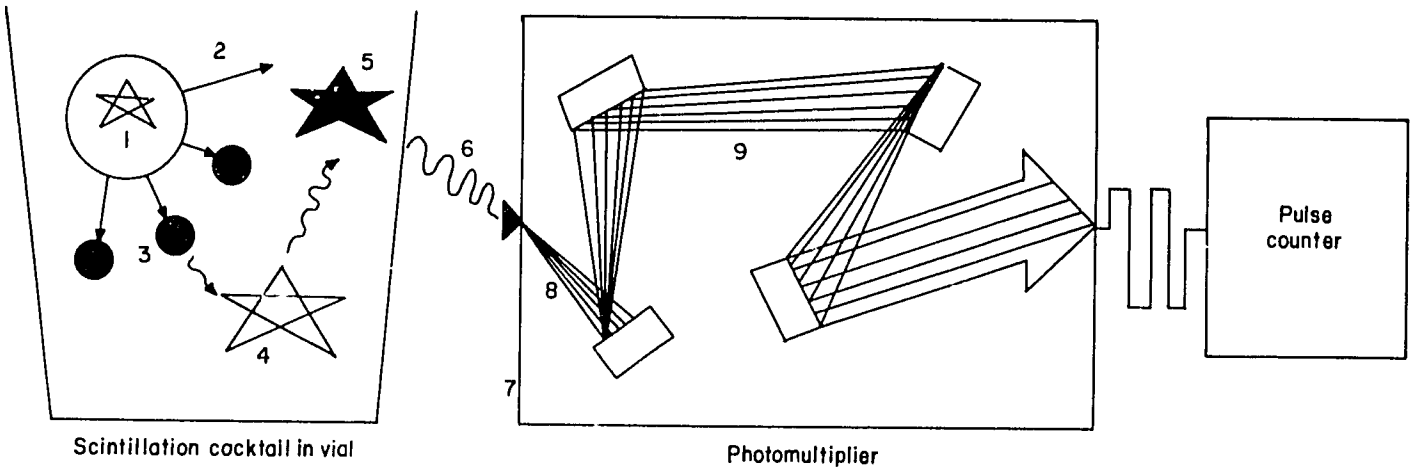
$$[(Z-X)/Y] \times 100 \qquad (2)$$

where:

X = quenched sample count (ct.min^{-1}),
Y = unquenched standard count (ct.min^{-1}), and
Z = quenched sample plus standard count (ct.min^{-1}).

The isotope in the standard must be the same as the one in the sample and it should

Figure 1. *Liquid scintillation and tritium detection.*



Legend:

1. Radioisotope
2. β emission
3. Excitation of solvent
4. Energy transfer to primary fluor
5. Energy transfer to secondary fluor
6. Photon emission
7. Photocathode
8. Photoelectron emission
9. Photoelectron amplification

Source: Adapted from Wallac LKB (1977).

not itself be quenched, so that non-quenching agents such as ^{3}H-toluene, ^{3}H-n-hexadecane and ^{3}H-cholesterol should be used. Water and benzoic acid can also be used, but as they are both quenching agents very small volumes should be added. The internal standard count in the sample should be at least 10 times as high as the sample count alone (Whisman et al, 1960).

The method suffers from a number of drawbacks:

- Highly accurate pipetting of the standard is essential and minor errors are inevitable.
- The sample cannot be reused or recounted as it will be contaminated by the standard.
- Opening the vial to add the standard will result in evaporation, oxygen quenching and water absorption, all of which are likely to cause variations in the second count.
- Reorientation of the vial causes slight alterations in the geometry of the vial relative to the photomultiplier tube.
- The small change in volume (100 μl of standard is frequently added) may change the degree of quenching.
- The sample and the standard must be thermally equilibrated to prevent moisture from condensing in the vial.
- Additional time is required to count.

As a result of these disadvantages, the linked errors in the estimates of the sample and of the internal standard reinforce each other. Nevertheless, reasonable care will ensure that the method is the most precise estimate of quenching available (Rogers and Moran, 1966).

External standard ratio (ESR) method. Following initial counting the vial and sample are irradiated by an external source of gamma radiation (^{226}Ra or ^{137}Cs) which is housed in a 40-mm lead shield in the instrument. The principle behind this method is that gamma radiation can dissipate the energy of a photon via the Compton effect. The incident gamma radiation photon reacts with a planetary electron causing the ejection of a recoil, or Compton, electron which behaves like a β particle. Any quenching of the sample causes proportionate quenching of the Compton electrons, which are counted by an additional pulse-height analyser set to detect very high energy particles coming exclusively from the Compton electrons. A calibration curve must be prepared and this is then used to calculate the efficiency of counting in the unknown samples.

In modern counters, the external standard technique is fully automated, with the gamma source placed adjacent to the vial while counting is continued for a further minute. The three advantages of the method are that efficiency can be calculated in any sample irrespective of its radioactivity, it is rapid and it requires no further handling of the sample. However, the disadvantages are fivefold:

- The efficiency with which gamma radiation enters the vial can be variable
- Irreproducibility occurs since it is impossible to ensure constant geometry between the gamma source and the vial, due both to instrument limitations and to variations in glass thickness.
- It is highly sensitive to electronic fluctuations e.g. in voltage.
- In practice, Compton electrons do not behave exactly like β particles.
- The process giving rise to Compton electrons is mass dependent and hence volume dependent.

Owing to these disadvantages, the method tends to be the least effective of the three methods of quench correction (Rogers and Moran, 1966).

Sample channel's ratio (SCR) method. Quenching involves a shift in the overall spectrum of pulse heights (Figure 2). Liquid scintillation counters have different channels to count at different energy spectra, normally a narrow-window and a wide-window efficiency. The channel's ratio is the narrow-window efficiency divided by the wide-window efficiency. The ratio is constant for an unquenched isotope; it is therefore necessary to establish a quench calibration or channel's ratio curve in a series of standards of identical activity but different degrees of quenching (Figure 2). The ratio decreases as the quenching increases and the relationship is usually linear or curvilinear.

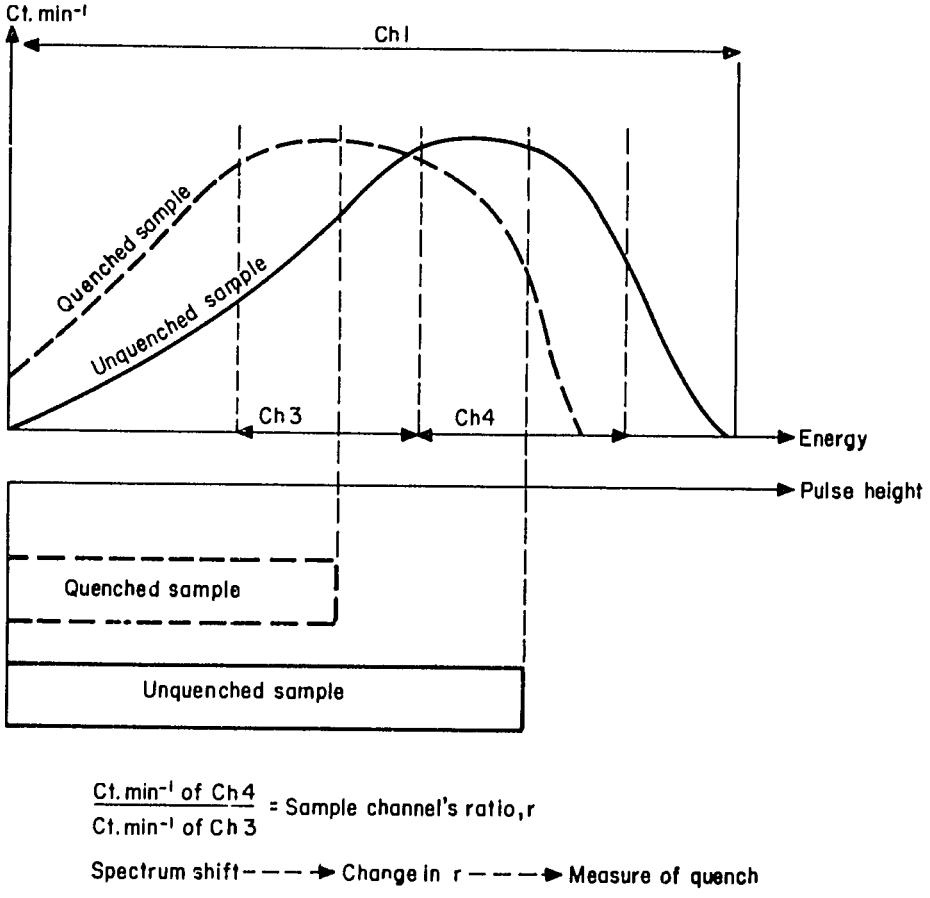
A major advantage of this method is that the sample to be counted does not need to be handled and can be reused as its composition is unaltered. For efficiencies down to 12%, the accuracy of the channel's ratio method is very similar to that obtained by internal standardisation (Rogers and Moran, 1966) but for highly quenched samples, its accuracy falls off sharply. The method is unsuitable where small amounts of radioactivity are present, as a prohibitively long time will be required to accumulate a statistically acceptable number of counts. In modern counters the SCR technique is frequently combined with the automatic ESR technique in a method known as the external standard channel's ratio (ESCR) method in which the ESR technique is used to check how good the scintillation cocktail is.

BIOLOGICAL SOURCES OF ERROR IN THE USE OF HTO

Tritiated water is used in two different ways. First, it allows an estimate to be made of body water and, indirectly, of body composition, following injection and equilibration based on the dilution principle. Second, by following the decline in activity over time, it is possible to calculate water flux, and this can be extended to measurements of milk or feed intake.

Nagy and Costa (1980) have examined the six assumptions that were made by Lifson and McClintock (1966) as fundamental to the use of HTO. These assumptions are particularly relevant to HTO work when fluxes are being measured; if they are invalid, significant errors in calculated water fluxes are likely. Nagy and Costa's examination of the six assumptions is regarded as of sufficient importance to be discussed in detail.

Figure 2. *Channel's ratio method: The effect of quenching on energy and pulse height spectrum.*



Source: Adapted from Wallac LKB (1977).

Body water volume

When calculating water flux, it is convenient to assume that body water volume is constant over a given period of time. This means that the animal is neither gaining nor losing weight, nor altering its body composition. Under field conditions this is seldom the case, particularly with growing animals, and the calculations must take into account such changes.

Constant water flux rates

The equations used to determine flux rates assume that the rate of flux and hence body water volume are constant. In fact they are not, since almost all influx and efflux events (drinking, eating, defaecation) are both independent of each other and sporadic. Major changes can occur especially under intermittent watering when cattle have been recorded as drinking up to 104 litres of water in 4 minutes (Nicholson, 1985). Such changes can greatly upset flux calculations, unless sampling times are adjusted to watering times (see page 15). Errors as a result of injudicious sampling times can vary from -2 to + 14.4% of true flux rates (Nagy and Costa, 1980).

Isotope labelling

Water molecules freely dissociate and their hydrogen (H) atoms exchange with the H atoms of organic molecules, or become incorporated with newly synthesised molecules (Culebras and Moore, 1979). Incorporation of the isotope into non-aqueous compounds will cause an overestimate of body water volume if exchange occurs prior to equilibration, and a higher calculated flux rate if exchange is relatively slower. Lewis and Philips (1972) found that it took

5 days for non-aqueous and aqueous ^3H to equilibrate in neonatal calves. They also reported that bound ^3H was sufficient to label 3.5% of body weight. The overestimate of body water volume by isotopic exchange alone can be as high as 13% since appreciable amounts of ^3H have been found in desiccated tissue (Nagy and Costa, 1980), although Richmond et al (1962) reported that exchange was usually no more than 2%.

Loss of ^3H to non-aqueous compounds is regarded as a source of significant error in growing animals and in animals with low water flux rate. When water flux alone is being calculated it is advisable to wait several days until ^3H exchange is complete prior to taking the first sample. However, when specific activity becomes very low in the animal's body water, as may occur at the end of a water flux trial, the process is likely to reverse and specific activities rise again as ^3H reenters the aqueous phase. To avoid this the specific activity of the end sample should not approach 1% of the activity of the first sample (Nagy and Costa, 1980).

A further error can be caused by the loss of HTO prior to equilibration, and although it is possible to extrapolate back to the time of injection using subsequent turnover rate, this is not necessarily valid since pre-equilibration turnover rate will be slow (due to fasting) and because the behaviour of HTO on injection is unclear. Failure to allow complete equilibration will give rise to errors (see page 15). In dehydrated camels for example, 18 hours may be required for equilibration (Seibert and Macfarlane, 1971). Nagy and Costa (1980) therefore recommend that workers report equilibration time in their studies.

Loss of non-aqueous bound tritium

The flux rate assumes that ^3H is lost only as HTO. It has been found that while the loss of bound ^3H in the dry matter of faeces and urine amounted to only 1% in kangaroo rats (Siri and Evers, 1962), such losses could be higher (although probably still quite small) in ruminants due to comparatively low digestibilities and the fact that each unit of cellulose has three exchangeable atoms (Nagy and Costa, 1980).

Isotopic and biological fractionation

The HTO method assumes that the concentration of ^3H in the water lost is equal to its concentration in the body. Studying dehydration in zebu cattle, Nicholson (unpublished results) counted faecal water in a cow 6 hours after she had drunk 80 litres of water and found that specific activity in the faeces was lower than in the blood. A similar finding was reported by McClintock and Lifson (1958). The workers in both studies concluded that since much of the water drunk continues down the alimentary tract, and since rates of faecal water loss rose rapidly within a few hours of drinking, the HTO in the body water did not have sufficient time to equilibrate fully with water in the alimentary tract prior to defaecation. Although Lifson and McClintock (1966) provide an adjustment equation for this unequal loss, under field conditions it is not possible to correct for this error unless total faecal and urine collections are made as part of the experiment.

Since ^3H atoms are much heavier than H atoms, the rate of loss of ^3H atoms (or HTO) by evaporation may be less than that of H atoms from normal water molecules. In an ingenious experiment using toads, Nagy and Costa (1980) found that this isotopic fractionation yields a 4.7% underestimate of the rate of water efflux by evaporation and a 9% underestimate when evaporation was from a glass beaker, the difference being attributable to 'effective' fractionation. The likely error varies according to animal species and the site and process of evaporation. For example, Rubsamen et al (1979) found that HTO levels in the pulmonocutaneous vapour of rabbits were between 5 and 50% lower than in the blood, but Nagy and Costa (1980) concluded that it is difficult to keep pulmonary vapour free from unlabelled contaminated water vapour.

Cutaneous and pulmonary water influx

Another assumption in the calculation of water flux is that unlabelled water from outside is not exchanging with labelled water. However, Nagy and Costa (1980) found that influx of water via the skin and lungs overestimated actual water influx rates, due to a constant exchange of unlabelled and labelled water. Nevertheless, this appears to be of importance only in insects and very small animals, particularly burrowing animals, in humid environments. Although probably not important in ruminants, Nagy and Costa (1980) regard this as the largest unavoidable source of error (up to ± 50%) in HTO measurement of water flux.

APPLICATIONS OF HTO IN LIVESTOCK RESEARCH

In livestock research HTO is used to estimate body water, body composition, water turnover, milk intake and feed intake.

Body water estimation

Although most animals have a fairly narrow range of body water space (% of body mass that is water) there are occasions when measurements of body water volume *per se* are required, as for example in dehydration studies. It is important to make it clear that using HTO gives estimates of body water space, and that HTO usually overestimates water space (Little, 1983; King and Finch 1982; King et al, 1978) and hence water flux rates.

Body composition

An extension of body water estimation is the fact that the more fat an animal carries the less its total body water space is, so that comparisons can be made based on a single injection of HTO and sampling at equilibration between individuals or groups of animals. In both body water and body composition estimation HTO space is being measured, and for reasons stated earlier this is not synonymous with total body water space, although HTO space is likely to be ± 20%, but usually ± 10%, of the true value.

In hydrated animals there is an inverse relationship between total water space and total body fat. Pace and Rathbun (1945) suggested a simplified formula for calculating body-fat content, based on the assumption that body-water content is constant at 73.2% of fat-free tissue. However, since gut water can be a substantial source of body water, this equation does not hold (Widdowson, 1968). Using the results of various workers, Little (1983) cited the empirical relationships between fat and body

water, and reference should be made both to this author and to Panaretto (1963). Caution should be exercised when predicting body-fat content from body-water content, not least because HTO is not an absolute measurement of total body water as validated by dissection.

Water turnover

Different animal species or animals in different environments have different rates of water turnover. Tritiated water allows measurement of this flux through the fractional rate constant, which is described by the equation:

$$k = \frac{\ln (H_1^*/H_2^*)}{t} \qquad (3)$$

where:

H_1^*, H_2^* = initial and final specific activities of the isotope in the animal, and

t = time interval (days).

In units of ml $H_2O.kg^{-1}.day^{-1}$ this is transformed to:

$$\text{ml } H_2O \text{ flux}.kg^{-1}.day^{-1} = \frac{1000\ Q \ln (H_1^*/H_2^*)}{W} \qquad (4)$$

where:

Q = the HTO space, and

W = the animal's weight (kg).

This equation assumes a steady-state model where Q is constant. In such a case:

H_2^* = half the activity H_1^*,

$\ln (H_1^*/H_2^*)$ = 0.693, and

$T_{\frac{1}{2}}$ = biological half-life calculated as:

$$T_{\frac{1}{2}} = \frac{0.693}{k} \qquad (5)$$

When Q is not constant, equations 17 and 18 apply.

Milk intake

The water intake of suckling livestock will be directly proportional to the milk intake when they are neither drinking water nor eating any food apart from milk. In addition to the water turnover, a qualitative analysis of the milk is required, both in terms of total solids and proportions of lactose, fat and protein, to allow calculations of metabolic water to be made (Coward et al, 1982a). Milk intake has been successfully estimated by the water turnover method using HTO in growing calves over prolonged periods of time, and this allows simultaneous measurement of body composition (Yates et al, 1971; Macfarlane et al, 1969).

Milk intake by older livestock that are still suckling can be estimated through the dam efflux method (Coward et al, 1982b). The mother is injected and the efflux of HTO is measured by sampling dam and offspring over a period of time. A two-compartment (mother and offspring) steady-state model describes water fluxes (Figure 3), and the fractional rate constants (Shipley and Clark, 1972) in dam and calf are given as:

$$\frac{H_m^*(t)}{H_m^*(o)} = e^{-k_{mm}t} \qquad (6)$$

and

$$\frac{H_c^*(t)}{H_m^*(o)} = \frac{F_{cm}(e^{-k_{mm}t} - e^{-k_{cc}t})}{Q_c(k_{cc} - k_{mm})} \qquad (7)$$

where:

H_m^*, H_c^* = specific activities in the mother's milk and the calf plasma, corrected for background activity,

Q_c = the HTO space of the calf,

F_{cm} = water flux from the dam to the calf,

k_{mm}, k_{cc} = fractional rate constants ($k_{mm} = F_{om} + F_{cm}/Q_m$ and $k_{cc} = F_{oc}/Q_c$), and

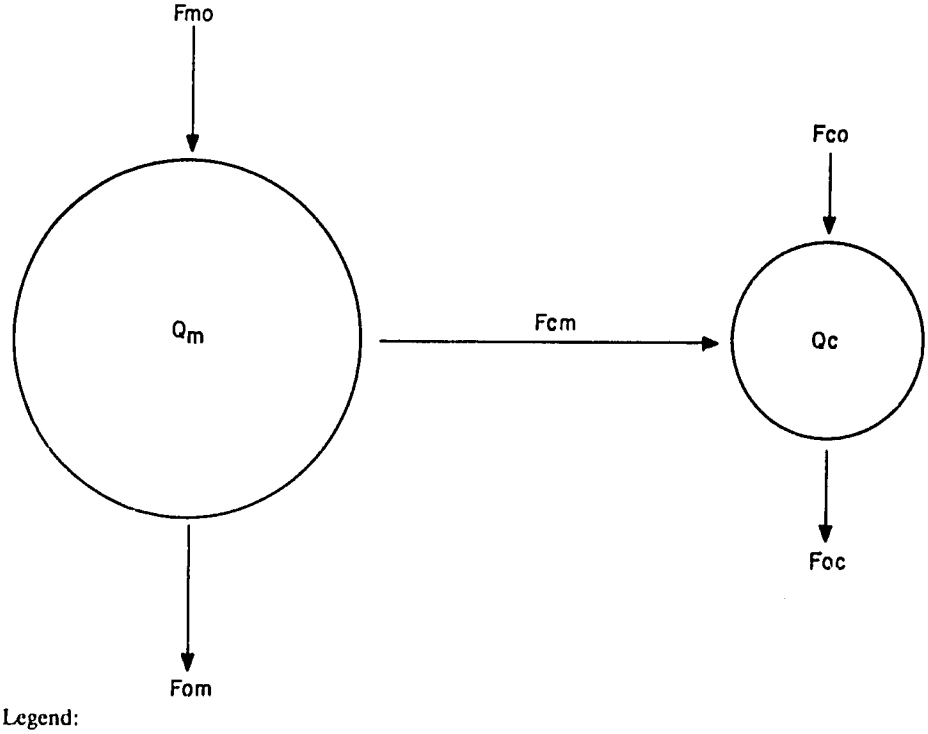
k_{mm}, $H_m^*(o)$ = slope and intercept of the mono-exponential curve for the disappearance of ^3H from the dam's milk.

Measured specific activities must be analysed by a computer program which fits numerical data directly to the compartmental model (Feldman, 1977). Since a steady-state does not exist in growing animals due to the changes in total body water and flow rates, the analysis initially requires that the estimates for unknown parameters be primed and subsequently refines them to converge on best-fit values.

Feed intake

Dry matter (DM) intake can be determined quite accurately from the water influx rate provided that the diet consists of <70% DM (Nagy, pers. comm.) and preformed water in the diet is the basis of the calculations. The calculations are extremely sensitive to small errors in DM estimates: in dry diets water influx from other sources (metabolic water, pasture or cutaneous exchange) is likely to have a major effect on estimated DM intake.

Figure 3. *Steady-state model of water fluxes in mother(m) and offspring(c).*



Legend:

Q_m, Q_c = estimated body water volume (HTO space) of dam and calf respectively;

F_{mo}, F_{co}, F_{om}, F_{oc} = directional water fluxes with second subscript indicating where is water coming from and first referring to where it is going.

Source: Adapted from Coward et al (1982a).

Metabolic water in non-drinking animals (where metabolic water is a constant fraction of total water flux) can be estimated from total water flux described by Nagy's (1975) equation:

$$\text{ml } H_2O_M \cdot \text{day}^{-1} = \frac{\text{ml } H_2O_M/\text{g food}}{\text{ml } H_2O_M/\text{g food} + \text{ml } H_2O_P/\text{g food}} \cdot \text{ml } H_2O_T \cdot \text{day}^{-1} \quad (8)$$

where subscripts M, P and T denote metabolic, preformed and total water.

Metabolic water per gram of food can be measured or calculated from oxidation yields of basic food components: 1 g each of protein, fat and carbohydrate yields 0.41, 1.07 and 0.55 ml water respectively on complete oxidation (Bergmann et al, 1974).

Benjamin et al (1975) used HTO dilution and standing biomass estimations to measure the intake of young barley by sheep. He found that the measurements from the two methods differed by less than 18%, and concluded that the HTO method was a useful field technique. Dry matter intake (DMI) was estimated as:

$$DMI = \frac{a}{b} \times c \quad (9)$$

where:

a = water turnover (litres.sheep^{-1}.day^{-1}),
b = water content (%) of food, and
c = DM content (%) of pasture.

The experiment could be refined to avoid errors due to dew, pasture growth and the varying DM content of the grass, but where this is not possible food intake can be satisfactorily determined by the HTO method.

METHODOLOGY OF HTO USE

HTO availability

Tritiated water is available in a variety of specific activities from Amersham International PLC, White Lion Road, Buckinghamshire, England HP7 9LL. A practical amount is 0.2 ml with an activity equivalent to 185 GBq.ml^{-1} (5 Ci.ml^{-1}).

Dose and toxicity

Opinion varies as to optimum dose to be used but generally, the smaller the dose the better. The most important criterion is that the sample taken at the end of the experiment should have a level of activity measurably higher than the background radiation. The author of this paper considers equilibration levels of 3.7 kBq.ml^{-1} (100 nCi.ml^{-1}) of body water a convenient rule of thumb. In some small animals a larger dose is required due to the small blood sample (Nagy and Costa, 1980), and 37 kBq.ml^{-1} (1 μCi.ml^{-1}) would be most appropriate. For body water and body composition studies, 370 Bq.g^{-1} body mass (10 nCi.g^{-1} body mass) or less are adequate in large animals since only one sample is needed. For body water turnover and milk intake studies, a high level of HTO concentration is required, especially in the dam efflux method because after 20 days the HTO in the cow's milk is further diluted in the calf's plasma.

Both HTO and HDO are toxic in high concentrations due to the 'heaviness' of water and radiation. The ionising radiation is a function of dose and its biological (as opposed to chemical) half-life. Radiation dose is given as:

$$Gy = 1.0973 \times 10^{-4}\, C^* T_{1/2} \quad (10)$$

where:

Gy = radiation dose in grays (Gy),
C* = initial specific activity in kBq.g^{-1} body mass, and
$T_{1/2}$ = biological half-life.

For a 300-kg cow injected with 740 MBq (20 mCi) HTO with a biological half-life of 4 days the dose per gram would be 1.1 x 10^{-3}Gy. This is 0.07% of a dose needed to induce acute effects and 0.7% of the threshold for chronic effects (impaired fertility, cancer etc) (Pizzarello and Witcofski, 1967). Seven-hundred-and-forty MBq of HTO injected into a 400-kg cow is about 0.05% of the maximum suggested non-injurious dose of 3.7 MBq.g^{-1} body mass (Feinendegen, 1967).

To avoid errors due to isotope decay, all the animals in a trial should be injected with the same batch of HTO. Similarly, all samples must be counted together. In practice, owing to the relatively long half-life of ^{3}H, several weeks must elapse before lower counts due to decay significantly affect the result. If necessary, decay correction can be calculated for samples not analysed simultaneously using the equation:

$$\ln H^*_{2c} = \ln (H^*_1 + k_d t_a) - \ln (H^*_1/H^*_2) \quad (11)$$

where:

H^*_{2c} = the corrected H^*_1,
k_d = the rate of tritium decay (1.53 x 10^{-4} disintegrations.day^{-1}), and
t_a = the time between the analyses of H^*_1 and H^*_2 (not the time between taking the samples).

Alternatively, a standard can be counted on each occasion a sample is analysed.

Stock solution

In a fume cupboard, the contents of a 0.2 ml vial with a concentration of 185 GBq.ml^{-1} (5 Ci.ml^{-1}) are made up to 200 ml with physiological saline solution (0.09% NaCl) to give an activity of 185 MBq.ml^{-1} (5 mCi.ml^{-1}). For small animals, a stock solution can be made up to 1 litre, giving an activity of 37 MBq.ml^{-1} (1 mCi.ml^{-1}). To store the solution, add a drop of toluene and keep in coloured glass bottles at 4°C or in smaller plastic bottles in the refrigerator. Label each bottle with date of manufacture so that decay can be calculated. Make up enough of both stock and standard solutions for all trials in a study, because small differences in dilution between standards could be a further source of error. An aliquot of stock solution is injected into the animal and the sample taken after equilibration is compared with the standard.

Standard solution

To prepare standard solution the stock solution should be diluted by a similar order of magnitude as it will be diluted when injected into the animal.

Example : A cow of 286 kg will be approximately 70% water. So if 5 ml of stock HTO (185 MBq.ml^{-1}) is injected into that animal, the dilution will be:

	DILUTION
5 ml into 286 x 0.70 x 1000 ml =	1:40 040

The preparation of the standard is as follows:

a) 0.2 ml stock HTO (185 MBq.ml^{-1}) is made up to 0.5 litre with physiological saline (0.09 NaCl) into a standard solution of 74 kBq.ml^{-1}. 1:2500

An ultra-micropipette previously calibrated by weighing or by a known weight of stock should be used to weigh the components to the nearest 0.1 mg in order to obtain maximum precision in the preparation of the standard.

DILUTION

b) 0.2 ml standard solution (74 $kBq.ml^{-1}$) + 3.0 ml background plasma or fat-free milk. 1:40 000

The dilution factors must be altered according to circumstances. For example, for a 40-kg goat injected with 1 ml of stock HTO with a concentration of 37 $MBq.ml^{-1}$, the dilution will be:

1 ml into 40 x 0.7 x 1000 ml = 1:28 000

The preparation of this standard will be:

c) 0.2 ml stock HTO (37 MBq. ml^{-1}) made up to 1 litre gives a standard of 7.4 $kBq.ml^{-1}$ 1:5000

d) 0.2 ml standard solution (7.4 $kBq.ml^{-1}$) + 0 8 ml background plasma 1:25 000

The concentration of the standard should be ± 20% of the expected dilution in the animal.

Injection of the animal with HTO

Unless the experiment is designed to investigate aspects of dehydration, the animals should normally be hydrated, although it is usual to withhold food and water for 8 to 12 hours before injection in order to avoid losses of HTO in the urine and faeces prior to equilibration and to prevent labelling of water which is not strictly body water in the food. Preferably, the animals should be injected at 1800 h so that equilibration can take place overnight without the risk of excessive water (and hence HTO) loss through evaporation.

Before injecting the animal, a background blood sample should be taken using an evacuated tube to which an anticoagulant has been added (lithium or sodium heparin are suitable). The injection syringe with needle and its cover should be weighed to the nearest 0.1 mg before and as soon as feasible after injection to prevent evaporation of residual HTO. When administered intramuscularly care should be taken to avoid blood vessels so as to prevent bleeding with possible loss of HTO on withdrawal of the needle as well as contamination of the needle with blood. The difference between the full and empty syringe weights is the volume injected.

Route of administration and equilibration time

In theory, HTO injected into the body of an animal will equilibrate after a certain number of hours. The author prefers the intramuscular route of injection for two reasons. First, HTO injected intravenously causes an immediate rise in specific activity in the blood, and second, since samples are drawn from the bloodstream, an 'equilibration' sample taken prematurely could have abnormally high levels of specific activity. The opposite, of course, could be said of the intramuscular route. However, intravenous administration is more likely to cause losses of specific activity in the urine as some diuresis will be occurring in the early stages of water deprivation. Since urine and faeces are likely to be voided prior to taking the equilibration sample, the smaller the loss of unequilibrated HTO via these routes the better.

Equilibration is a function of body weight and may vary in time from 1 hour in lambs to between 10 and 18 hours in camels. Once equilibration has been reached, and provided no food or water is offered, HTO levels will remain constant as it is assumed that ^3H leaves the body at the same rate as unlabelled water. Although this is a questionable assumption, for practical purposes 12 to 14 hours post-injection is a satisfactory interval for taking an equilibration sample from cattle. The animal should be weighed at equilibration and can then resume normal eating and drinking.

If there is any doubt about equilibration time, it is better to take two samples an hour or two apart. The sample with the highest activity will then be the equilibration count.

End sample

At the end of the trial, a blood sample is taken in order to calculate water turnover, and the animal is reweighed. For cattle, 10 to 20 days after the trial is a suitable period for calculating water turnover. An animal with a slower water turnover would still have a countable activity up to 30 days after the trial, so there is no reason why the period should not be flexible to suit the convenience of the operator.

When working with infrequently watered stock, care should be taken to adjust the timing of the end sample to watering time. For example, measuring water turnover in 3-day watered cattle involves injecting them on the night before they are normally watered and taking an equilibration sample an hour or so before watering. This gives the HTO space of a dehydrated animal. Water consumption is recorded and the hydrated HTO space (expressed in %) is calculated using the equation:

$$\text{Hydrated HTO space} = \frac{\text{HTO space} + I}{W_2} \times 100 \quad (12)$$

where:

HTO space = tritiated water space (litres) of a dehydrated animal,

I = water consumption (litres), and

W_2 = rehydrated weight (kg).

The end sample is taken 9, 12, 15 or 18 days later prior to watering. If the animal is watered first, not only will its water turnover rate be affected, but HTO will be unequilibrated unless several hours are allowed for the equilibration of residual activity with ruminal water.

However, since HTO space overestimates total body water (TBW) space in large ruminants, relying on a validated regression equation may be more useful in determining true TBW change between dehydration and rehydration. In validation studies in cattle, Little (1983) found the relationship between HTO space (litres) and TBW space (litres) to be:

$$TBW = 0.78\,HTO + 7.96 \quad (13)$$
$$(r = 0.98, SE_b = 0.058)$$

Having converted HTO space to TBW space for a dehydrated animal, we can now calculate the TBW space of a rehydrated animal as follows:

$$TBW_r = \frac{TBW_d + I}{W_2} \quad (14)$$

where:

TBW_r = rehydrated TBW space (litres),

TBW_d = dehydrated TBW space (litres), and

I = water consumption (litres).

Thus if a 300-kg cow with a TBW_d of 198 litres (66% of fasted liveweight) drinks 67 litres of water, her TBW_r becomes 265 litres, which is 72% of fasted liveweight

Since body composition or body water volume may change over the trial period,

HTO space can be recalculated at the end of the trial using another dose of HTO followed by sampling. This dose can be very small since only an equilibration sample will be required.

Sample preparation

Blood should be centrifuged immediately after sampling and plasma transferred either into sealed bottles or directly into counting vials in order to avoid spontaneous haemolysis and further colour quenching.

Plasma should be refrigerated or frozen. Freezing can cause precipitation of some proteins, so an accurate determination of the plasma solid concentration of the supernatant is necessary. In any event, plasma solids must be determined gravimetrically at 60°C.

The commonest methods available for sample preparation and subsequent counting are vacuum distillation, acid precipitation, ethanol precipitation and direct sample counting.

Vacuum distillation

In the early days of HTO work, vacuum distillation was the customary method of HTO counting (Till and Downes, 1962). It involves distillation of water from the plasma using Thunberg tubes, dry ice, ethanol and a vacuum apparatus. If the equipment is available, vacuum distillation has the great advantage of separating water from protein avoiding both dilution or quenching agents. The method is time-consuming but accurate even though it can cause isotopic fractionation (Riley and Brooks, 1964). Although vacuum distillation has largely been replaced by other methods (Springell, 1969), it is still occasionally and successfully used (Little, 1983).

Protein precipitation by acid

Using 10 to 20% TCA (trichloroacetic acid) to coagulate plasma proteins, and centrifugation to separate the coagulated proteins from the plasma, this method gives a clear supernatant for counting. One of its disadvantages is that although colour quenching is reduced, chemical quenching may be increased by the acid. In addition to the error inherent in any dilution technique, the rapid coagulation of the proteins can cause plasma trapping, which means that some activity fails to reach the acid–water supernatant. This will give rise to a lower count and an overestimate of body water. However, accurate pipetting and crushing of the coagulated protein pellets to release trapped HTO will overcome the problem. Nicholson (unpublished results) used 2 ml of sample to 1 ml of TCA and found that when the coagulant was crushed, the method proved to be the most suitable for preparing a sample for counting.

Protein precipitation by ethanol or acetone

Plasma proteins can also be precipitated by ethanol or acetone. Plasma is mixed with 96% ethanol in Nunc tubes and spun at 10 000 rpm at -20°C. The method suffers from the same disadvantages as the acid precipitation technique, but its precipitate is easier to resuspend in order to count residual activity. Acetone is not recommended as it is a strong quenching agent. Both the ethanol and acetone methods and the acid technique indicated some residual activity in the precipitate after washing and resuspending (Nicholson, unpublished results).

Direct sample counting

Water-based biological material can be counted directly if solubilising agents, detergents or more sophisticated solvents are added to the sample. Provided that a suitable quench correction procedure is adhered to, this method overcomes the problem of dilution errors. However, a protein precipitate occurs in the counting vial which, if shaken or disturbed, greatly increases quenching.

Counting

Before counting begins, 4.5 ml of scintillation cocktail is added to 0.5 ml of sample (not the other way round). This sample-to-cocktail ratio (or 'counting geometry') is critical, and advice should be sought from the manufacturers of the scintillation counter on the correct ratio. If the quantity of radioactive sample is very small, absorption of the sample onto the glass walls of the counting vial can produce a change from 4 to 2 pi geometry and this may result in a highly significant change in counting efficiency (Davidson and Oliveiro, 1965). Duplicates are necessary and new pipette tips must be used for each pair of samples.

For plasma pipetting, the 'reverse' technique of micropipetting is recommended since this reduces volume errors due to plasma viscosity. The technique involves complete expulsion of the air to the second stop, pipetting the sample and expelling to the first stop.

Having mixed the sample with the cocktail, the mixture will be scintillating. At this stage, photons may be produced as a result of the chemical reaction releasing extra energy in the form of single photon events (Wallac LKB, 1977). This chemiluminescence can be avoided by one of three options:

- Cooling the vials to 4°C for a period of 1 hour to several days until cloudiness has disappeared;
- Adding 0.5 to 1.0 ml of 0.5 M HCl to acidify the sample;
- Heating the vials to 35°C for 2 to 3 hours to speed up the chemical reaction, cooling and subsequent counting.

Quench correction

Use either the internal standard or the external standard channel's ratio method to correct for quenching. For the internal standard method, count 100 ml of high-activity HTO or ^{3}H toluene in sextuplicate. The main source of error will be the volume added to the cocktail. The mean count of the six vials should be used for efficiency determination (equation 2).

For the ESCR method it is necessary to obtain the background count (ct.min^{-1}) from six replicates of the material to be counted. The procedure is then as follows:

- Add one ^{3}H capsule of known activity (about 2 x 10^{5}d.min^{-1}) to 100 μl of unlabelled plasma and 4.7 ml of scintillation cocktail. This is the *standard* sample.
- Program the scintillation counter computer as per manufacturer's instructions with counting time, mode, capsule activity, decay correction coefficient, operating channels, mean background count etc.
- Count the standard sample, pipette 5 μl of CCl_4 into it and recount.
- Add 10, 20 and 30 μl of CCl_4 to the standard sample and recount after each addition. There are now five standard points and the computer will

automatically calculate the quench curve and print it out (Figure 4).

- Start counting the samples. The computer will automatically calculate $d.min^{-1}$, which must be used in all calculations, and the efficiency ratio.

The standards are made by adding standard solution to a known volume of unlabelled material. Since unlabelled material will contain a significant amount of background radiation, this must be measured and deducted from the gross activity of the labelled material.

Body water volume (Q, in litres) is estimated from the following equation:

$$Q = \frac{H_s^* \times \text{Vol injected} \times \text{Dilution factor}}{H_1^* \times 1000} \quad (15)$$

where:

H_s^* = net count of the standard ($d.min^{-1}$), and

H_1^* = net count of the equilibration sample ($d.min^{-1}$).

The net count of the standard must be equated with the net count of the equilibration sample by adjusting for water content. Thus, if plasma is 92% H_2O, the standard will contain (0.9 ml x 0.92) + 0.1 ml standard solution = 93% H_2O, and the standard count must be adjusted down by multiplying by a coefficient of 0.99 (0.92/0.93). The volume of the standard can be different to the sample provided further adjustment is made for the differences in actual water volume. The HTO space turnover ($litres.day^{-1}$) is then calculated as follows:

$$\text{HTO space turnover} = \text{HTO space (\%)} \times k \quad (16)$$

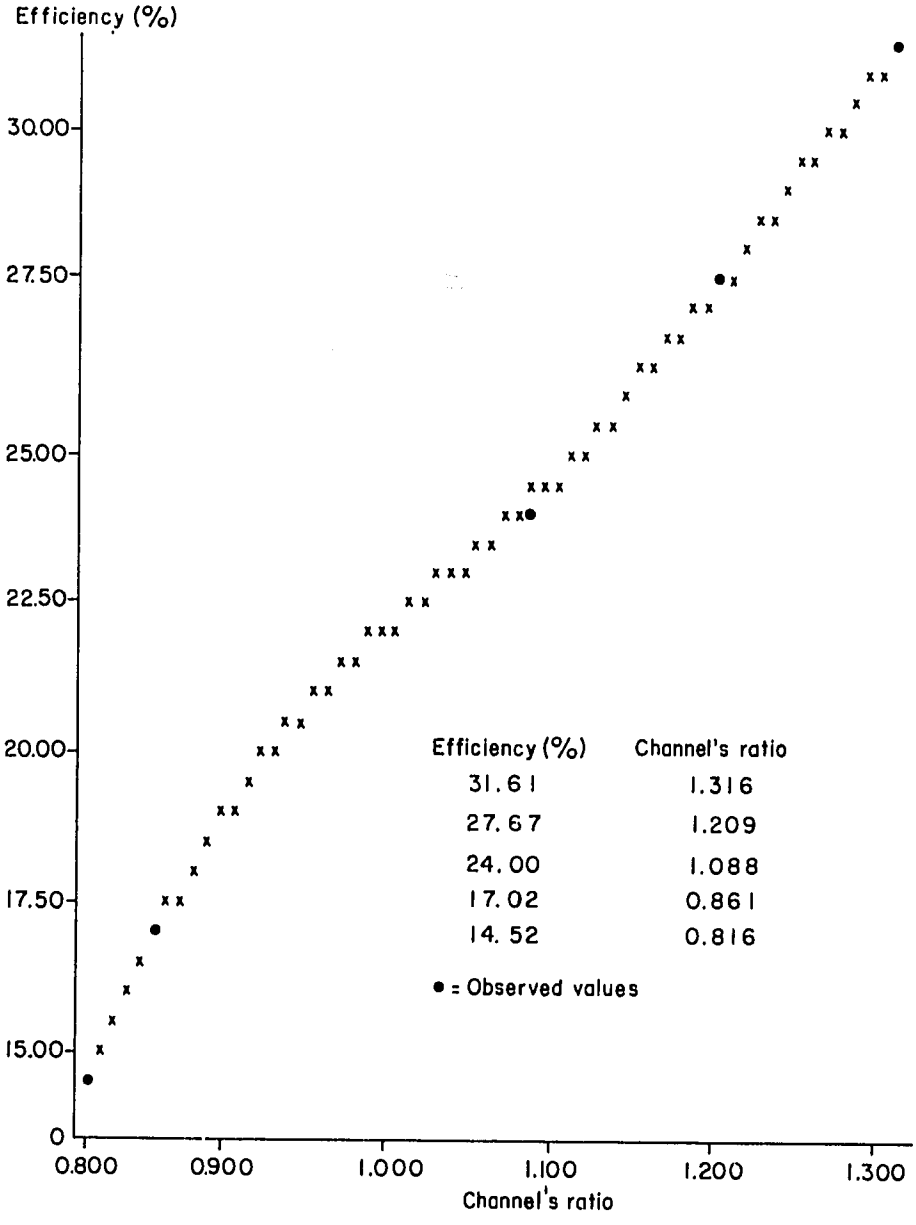
where:

$$\text{HTO space (\%)} = \frac{\text{HTO space (l)} \times 100}{\text{W (kg)}} \text{ and}$$

k = rate constant.

It is important to realise that HTO space is an estimate of body water volume and that if necessary, validation needs to be carried out.

Figure 4. *Quench calibration curve for acidified fat-free milk in pseudocumene prepared using manual serial addition of CCl_4; observed values joined using a spline function.*



Source: Nicholson (unpublished results).

Growing animals

Under steady-state conditions, turnover is equal to water influx which is equal to water efflux. For animals which are growing, or gaining or losing weight, $T_{1/2}$ is not the time required to turn over half the body water since body-water volume (Q) is not constant. Coward et al (1982a) showed that water influx in growing animals could be calculated from the equation:

$$\int_{t_1}^{t_2} F_{in}(t)\,dt = \frac{Q_1 - Q_2}{\ln \frac{Q_1}{Q_2}} \cdot \ln \frac{H_1^*}{H_2^*} \quad (17)$$

where:

$Q_{1,2}$ = initial and final HTO spaces (litres), and

$H_{1,2}^*$ = initial and final specific activities.

Nagy and Costa (1980) transformed Lifson and McClintock's (1966) equation for water influx by using body water (Q) changing linearly with time:

$$F = \frac{2000(Q_2 - Q_1)\ln(H_1^* Q_1 / H_2^* Q_2)}{(W_1 + W_2)\ln(Q_2/Q_1)t} + \frac{2000(Q_2 - Q_1)}{t(W_1 + W_2)} \quad (18)$$

where: F = water influx (ml H_2O influx.$kg^{-1}.day^{-1}$),

Q = body-water volume (litres),

$W_{1,2}$ = animal weights (kg) at two points in time, and

$\frac{2000(Q_2 - Q_1)}{t(W_1 + W_2)}$ = water stored.

In practice, equations 17 and 18 give similar estimates of water influx.

Using equation 18 and the equations by Green (1972) and Nagy (1972), Nagy and

Costa (1980) calculated the likely error involved in estimating water efflux. They found that the larger the change in body-water volume, the larger the error in efflux-rate estimation, particularly when body-water volume fell.

Worked example

Equations 15 and 17 can be used to calculate the milk intake by a growing calf, provided that the ratio of the variable input [F(1)] and output [F(t)] rates is constant. The following data are given:

W_1 = 66.75 kg

W_2 = 74 kg

H_1^* = 4750 d.min^{-1} (adjusted)

H_2^* = 1938 d.min^{-1} (adjusted)

H_3^* = 5521 d.min^{-1} (adjusted)

Composition of milk: 14.54% solids (including 5.4% fat, 3.3% protein and 4.9% lactose) and 85.46% water.

Using these data:

$$Q_1 = \frac{5521 \times 0.93 \times 1 \times 50\,000}{4750 \times 1000} = 54.05 \text{ litres}$$

where:

0.93 = correction factor for water content of standard,

1 = 1 ml HTO injected, and

50 000 = dilution factor.

At the end of the trial, body-water volume (Q_2) was found to be 62.9 litres. Thus the total water intake [$F_{in}(t)$] was:

$$\int_{t_2}^{t_1} F_{in}(t)\,dt = \frac{54.05 - 62.9}{\ln \frac{54.05}{62.9}} \cdot \ln \frac{4750}{1938} = 50.98 \text{ litres}$$

Complete oxidation of the milk will yield 9.83 g H_2O/100 ml milk, so that total water yield will be 85.46 + 9.83 = 95.29 g and the total milk intake by the calf would be 50.98 x 0.953 = 48.59 litres if the calf did not have any other source of water input. Validation done by weighing the calf before and after suckling over a 10-day period showed its milk intake to be 50.5 kg.

STATISTICAL GUIDELINES

Beta emission is a random process, such that an identical sample will not give exactly the same count over repeated counting periods. Similarly, replicates will not give identical counts so that, for samples of low activity in particular, counting time should be extended or a greater number of replicates used in order to get a better estimate of the true mean.

Radiotracer experiments use the relative standard deviation (relative σ which is defined as $100/\bar{x}$ where $\bar{x}$ is the mean count) to estimate the true mean. They are designed to have a relative σ of 1%, which means that it is necessary to have 10 000 counts per sample. Since decay follows a Poisson distribution, one can then state that there is a 68.3% probability that the base count is 10 000 ± 100. It follows that to obtain optimum accuracy it is better to count for a preset number of counts.

CONCLUSIONS

This comprehensive review of the use of HTO in animal experiments has been designed for workers in Africa, who have difficulty accessing the literature, especially some of the more specialised but obscure journals on radioisotopes. The HTO method has sometimes been abused because of a failure to grasp, or be aware of, the potential errors in the technique. These errors can be reduced by accurate experimentation, but only to a point where unavoidable biological and biochemical phenomena interfere with the distribution and exchange of tritium atoms. Nevertheless, the scope for its use in Africa is large over a wide range of applications, and it is hoped that this article will serve as a solid base, both theoretically and practically, from which to start.

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Molybdenum in soils and plants and its potential importance to livestock nutrition, with special reference to sub-Saharan Africa

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SUMMARY

SOILS IN sub-Saharan Africa are low to very low in available molybdenum (Mo). Soil pH, organic matter, clay content, drainage and nutrient interactions seem to be the main factors affecting the availability of Mo to plants.

In sub-Saharan Africa, response to applied Mo has been observed in groundnuts, cowpea, soya bean, maize and sugarcane. Molybdenum can be applied by seed treatment and soil and foliar applications. Liming may also increase the availability of Mo in acid soils. The development of Mo-deficiency symptoms in maize is related to the Mo concentration in the seed. No seed that contained more than 0.13 ppm Mo produced Mo-deficient plants.

High concentrations of Mo seldom retard plant growth, but levels of more than 10 ppm in feed seem to be toxic to ruminants. Molybdenum deficiency has never been reported in farm animals, and nutritional interest in Mo for animals is concerned with its toxic effects and its interactions with copper (Cu) and sulphur (S).

The role of Mo in legumes with respect to N fixation and its toxicity in forages grown on soils with prolonged wetness, high pH and saline-sodic conditions merit special attention.

INTRODUCTION

Schutte (1954) reported that the soils of sub-Saharan Africa are low in micronutrients. In a review of micronutrient investigations in West Africa, Kang and Osiname (1972) stated that B, Mo and Zn problems are of greater economic importance than those of Cu, Fe and Mn. In a more recent review of micronutrient problems in tropical Africa, Kang and Osiname (1985) concluded that these problems are less common in the humid zone than in the sub-humid and semi-arid zones.

Despite more than three decades of investigations on micronutrients, their role in the soil-plant-animal systems of sub-Saharan Africa has not yet been studied systematically. This is the first article in a planned series of reviews on micronutrients, and it summarises the role of Mo in soils and plants and its potential for livestock nutrition in sub-Saharan Africa, the aim being to provide background information for future work.

THE FUNCTIONS OF MOLYBDENUM IN PLANTS AND ANIMALS

Molybdenum is involved in several enzyme systems including nitrate reductase, xanthine oxidase, aldehyde oxidase and sulphate oxidase (Nicholas, 1975). Molybdenum is also required in the synthesis of ascorbic acid and is implicated in making iron (Fe) physiologically available in plants.

Xanthine oxidase or xanthine dehydrogenase, which is widely distributed in animals, and nitrate reductase in plants, are the only known Mo-containing metalloproteins. Nitrate reductase activity is reduced by Mo deficiency. Molybdenum also plays an important role in N metabolism in that it catalyses the fixation, by rhizobia in legumes, of dinitrogen gas to ammonia, which can be utilised by the host plant. The only known biochemical function of Mo in animals, other than its interaction with Cu, is in the formation and activity of xanthine oxidase.

DIAGNOSIS

Deficiency symptoms

Since Mo is closely involved in the N metabolism of plants, its deficiency resembles N deficiency. Molybdenum-deficient plants grow poorly, their leaves become pale and wither. Limp leaves are typical of Mo deficiency. The 'yellow spot' disease of citrus and 'whip tail' in cauliflower are well-known Mo-deficiency syndromes (Katyal and Randhawa, 1983).

Webb (1954) observed severe Mo deficiency in pot trials in Gambia. However, this was not confirmed in a field trial with groundnuts (Maremah, 1970). Molybdenum deficiency commonly occurs in the groundnut-growing areas of northwest Senegal (Martin and Fourrier, 1965), northern Ghana (Stephen, 1959) and northern Nigeria (Heathcote, 1970).

Using the sand culture technique, Aduayi and Idowu (1981) observed that at Mo levels of less than 1 ppm, okra (*Hibiscus esculentus*) leaves were pale yellow and curled upwards. At application rates between 1 ppm and 4 ppm Mo, plants were healthy with deep green leaves, while applying between 8 and 16 ppm Mo resulted in stunted plant growth and dark brownish coating on the roots.

Soil testing

Several methods for assessing available Mo in soils have been evaluated, but only three have been used widely. The best known is probably the use of Tamm's reagent (acid 0.275M ammonium oxalate, pH 3.3) proposed by Grigg (1953), who showed that the amount of oxalate-extractable Mo was significantly correlated with plant Mo content. The method involves only shaking and filtration, followed by determination of Mo in a very clear extract with minimum matrix interferences and without the need for any background correction in the instrument (Lombin, 1985a).

Lombin (1985a) observed that acid ammonium oxalate solution extracted slightly more Mo than did NaOH and much greater amounts than did anion-exchange resin (Table 1). Nigerian savanna soils are generally high in sesquioxides, and the greater capacity of the oxalate solution to remove soil Mo may be attributable to the breakdown of Fe oxides which contain soil Mo (Reisenauer et al, 1962).

The linear correlations among Mo uptake, NaOH Mo and NH_4-oxalate Mo and pH, organic matter (OM) and silt + clay contents, were all highly significant. Anion-exchange-resin-extractable Mo was poorly correlated with soil properties (Lombin, 1985a).

Anderson (1956) quoted Mo values critical for plant growth ranging from 0.04 to 0.12 ppm, while Grigg (1953; 1960) estimated values of between 0.14 and 0.20 ppm. Critical levels of Mo obtained by various extractants are shown in Table 2.

Lombin (1985b) reported that only two out of 30 Nigerian savanna soils contained more than 0.20 ppm Mo, the others ranging from 0.07 to 0.17 ppm. However, the relative yields obtained on the 30 soils cropped in the greenhouse did not reflect the apparent deficiencies: on six soils containing 0.075 ppm Mo, relative yields ranged from 75 to 85%, compared with a range of 89 to 136% for the remaining 24 soils. It would therefore seem that the critical level for these soils is below 0.1 ppm Mo.

Table 2. *Critical levels of Mo obtained by various extractants.*

Extractant	Extractable Mo (ppm)		
	Deficiency	Adequate	Excess/toxicity
NH_4 oxalate + pH correction	<0.01–0.02	—	>0.5–1.0
NH_4 oxalate (soil pH 5)	<0.1	0.1–0.2	—
NH_4 oxalate (soil pH 6)	—	0.1	>0.5

Sources: Reisenauer et al (1973); Sillanpää (1982).

Molybdenum availability is not routinely assessed anywhere, due to the difficulty of determining accurately very small quantities of Mo. More often, Mo availability is assessed by soil pH. Soils with pH values of more than 6.0 to 6.5 rarely require Mo (Katyal and Randhawa, 1983), although there are areas, for example the northern plains in China, where soils are alkaline but still deficient in Mo (Liu Zheng et al, 1983).

Leaf analysis

Molybdenum concentrations in plants vary from less than 0.1 ppm to more than 30 ppm. However, typical plant concentrations range between 0.1 and 0.2 ppm Mo. It is believed that crops will respond to Mo if they contain less than 0.1 ppm Mo (Katyal and Randhawa, 1983). Mwakatundu (1977) found that the average Mo content of East African pastures ranged from 0.09 to 6.6 ppm. In all locations where Mo was deficient in the pasture, grazing animals had deficient plasma Mo levels. Working with Nigerian savanna soils, Lombin (1985b) reported that on four soils where the relative plant yields dropped below 90%, the plant Mo concentration varied from 0.10 to 0.12 ppm compared with a range of 0.13 to 0.30 ppm for others.

Table 1. *Range and average values of extractable Mo in some Nigerian savanna soils, using three common methods of extraction.*

Method	Extractable Mo (ppm)		
	Range	Mean	SD
NH_4 oxalate	0.065–0.144	0.109	0.027
NaOH	0.050–0.160	0.092	0.025
Anion-exchange resin	0.023–0.109	0.055	0.018

Source: Lombin (1985a).

MOLYBDENUM CONTENT OF SOILS

Total Mo

Few data are available on the total content and distribution of Mo in African soils. Peyue (1963) reported very low total Mo contents (0.44 – 0.75 ppm) for Malian surface soils. Cottenie et al (1981) also found a wide range of total Mo contents (3 – 4.2 ppm) for selected Nigerian soil profiles.

Extractable Mo

Dabin and Leneuf (1960) determined the levels of Mo extractable with 2.5% acetic acid from 58 soils in the banana-growing areas of Ivory Coast. Except for the organic and hydromorphic soils, the rest of the soils were all low in Mo. Mwakatundu (1977) concluded that Mo is deficient in soils derived from sedimentary and metamorphic rocks and from Kainozoic rocks. Cottenie et al (1981), who studied the micronutrient status of selected soils from the humid zone of southern Nigeria and Togo, reported low levels of NH_4-oxalate-extractable Mo. Ibrahim (1982) found low levels of extractable Mo in three major soils in the Gezira scheme in Sudan.

As a part of a global study on soil micronutrients, Sillanpää (1982) investigated the micronutrient status of a large number of soils from Ghana, Nigeria, Sierra Leone, Malawi, Tanzania and Zambia. He reported generally low to deficient levels of Mo. The Mo levels found by Lombin (1985b) in Nigeria's semi-arid savanna soils are given in Table 3.

Table 3. *Extractable Mo in semi-arid savanna soils in Nigeria.*

Soil order	Extractable Mo (ppm) Range	Mean
Inceptisols	0.065 – 0.142	0.099
Alfisols	0.07 – 0.173	0.121
Oxisols	0.067 – 0.135	0.093

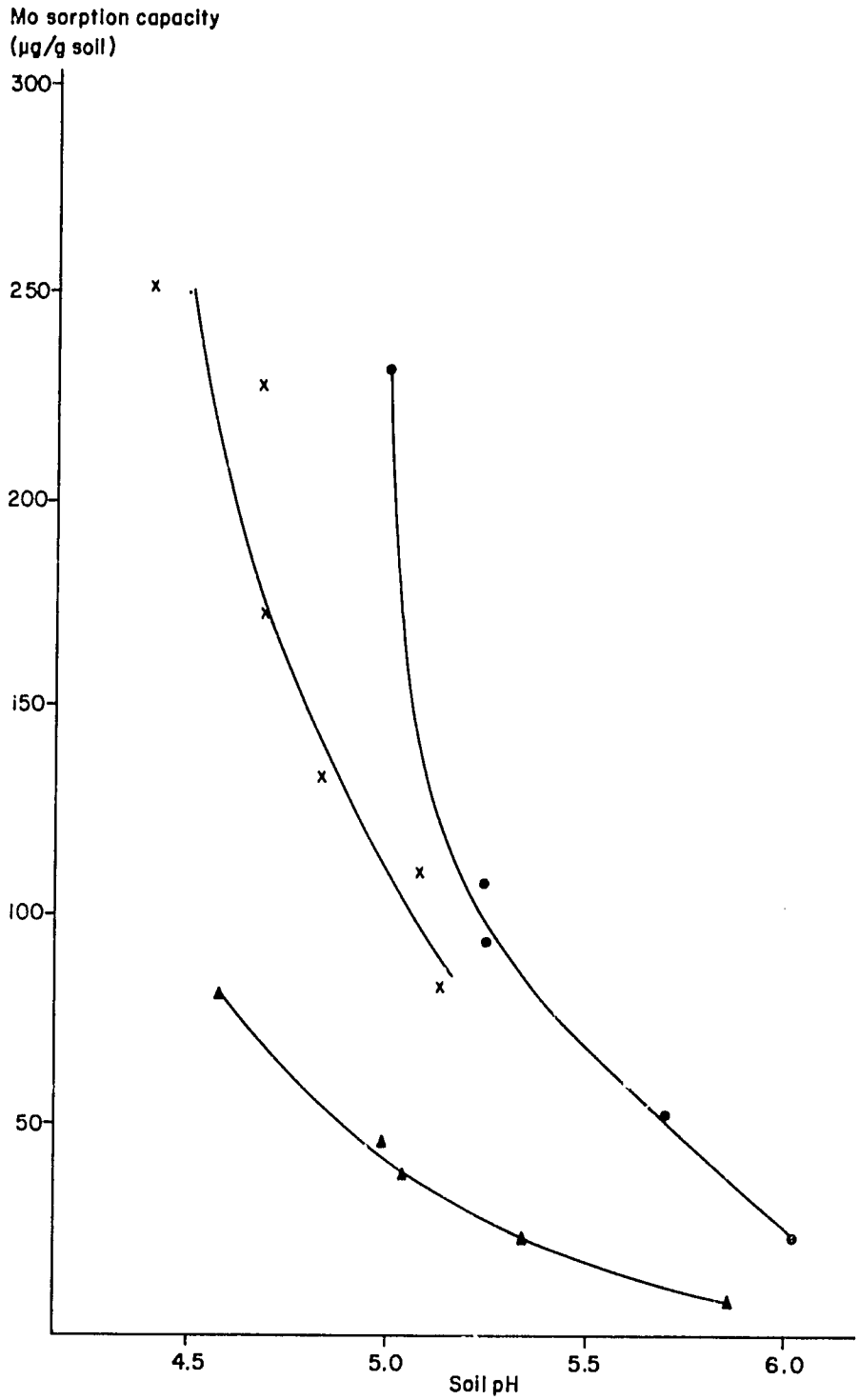
FACTORS AFFECTING AVAILABILITY OF MOLYBDENUM TO PLANTS

Soil pH

Soil pH is one of the most important factors affecting the availability of Mo to plants (Gupta and Lipsett, 1981). The MoO_4^{2-} concentration increases 100-fold for each unit increase in pH (Lindsay, 1972). With increasing pH, the amount of soluble MoO_4^{2-} species in equilibrium with soil Mo is much greater than for $HMoO_4^-$ and H_2MoO_4. At a pH of 5 or 6, the ion $HMoO_4^-$ becomes dominant and at very low pH values the unionized acid H_2MoO_4 and the cation MoO_2^{2+} are the principal species present (Krauskopf, 1972). The MoO_4^{2-} anion exists in an exchangeable form in the soil. Thus, the fact that Mo availability to plants increases with increasing pH may be explained by an anion exchange of the type $2\,OH^- \leftrightarrows MoO_4^{2-}$ (Berger and Pratt, 1965). Even wulfenite ($PbMoO_4$), the least soluble of soil Mo compounds, becomes more soluble as pH increases (Vlek and Lindsay, 1974).

Like PO_4^{2-} and SO_4^{2-}, the MoO_4^{2-} anion is strongly adsorbed by Fe and Al oxides, which markedly increase at low pH. As a result, Mo deficiency is normally a problem on acid soils. Tanner (1978a) reported that the values for Mo sorption capacity ranged from 6 μg/g in a sandy clay loam of pH 5.85 to 267 μg/g in a clay of pH 4.40 and averaged 175 μg/g. At each site there was a close inverse relation between Mo sorption capacity and soil pH (Figure 1). The sorption of Mo was significantly related to other factors such as exchange capacity and acidity, exchangeable Al and dithionite/citrate- and oxalate-extractable Fe. Lombin (1985b) reported that the amount of Mo removed by greenhouse peanuts and that extracted chemically were both well correlated with the pH of Nigerian savanna soils.

Figure 1. *Relationship between Mo sorption capacity and soil pH for three soils in Zimbabwe.*



Source: Tanner (1978a).

Organic matter

The level of available Mo has been found to be closely related to soil organic matter (Karimian and Cox, 1978). Lombin (1985b) reported that the amount of ammonium-oxalate-extractable Mo correlated significantly with organic matter content ($r = 0.52$, $P<0.01$). It is conceivable that the Mo tied up in organic matter will be released for plant use through mineralisation. It is also possible that Fe oxide

bound to organic matter may be responsible for Mo adsorption. However, since the West African savanna soils in general contain low levels of organic matter and the rate of mineralisation is high, only Mo complexed with organic matter may be unavailable to plants in the short term. This fraction is unlikely to limit Mo availability seriously under field conditions.

Clay

The role of clay in the micronutrient status of soils is well documented (Mortvedt et al, 1972; Davies, 1980). Lombin (1985b) reported that extractable Mo was significantly correlated with clay fraction. Using multiple regression, he also evaluated the relative importance of soil factors for Mo uptake by plants. The factors which contributed significantly to Mo uptake by peanuts are shown below in a descending order of significance in a predictive equation:

Mo uptake =
$0.33 + 5.87$ Ext Mo $- 1.90$ OM $+ 9.86$ C
$R^2 = 0.66, P<0.01$

where:
Ext Mo = extractable Mo
OM = organic matter content (%)
C = clay content (%)

Drainage

Soil wetness seems to be one of the main factors affecting the availability of Mo. Wet soils tend to have high organic matter content and large amounts of Mo that may be readily available (Kubota et al, 1961). Poorly drained soils accumulate so much MoO_4^{2-} that the plants grown on them are toxic to animals (Davies, 1956; Kubota et al, 1961).

Crop sensitivity

Table 4 lists crops according to their susceptibility to Mo deficiency. Crucifers and legumes have high Mo requirements. These crops are frequently affected by Mo deficiency on soils on which cereals may grow without suffering this deficiency (Katyal and Randhawa, 1983).

Nutrient interactions

Uptake of Mo by plants is usually enhanced by soluble P and decreased by available S (Gupta and Lipsett, 1981). The effect of P on increasing the concentration of Mo in plants seems to be associated with the stimulating effect of PO_4^{3-} ions on the uptake of Mo and the formation of a complex phosphomolybdate anion, which is absorbed more readily by the plants (Barshad, 1951).

Table 4. *Relative susceptibility of crops to Mo deficiency.*

Susceptible	Moderately susceptible	Tolerant
Alfalfa	Cabbage	Apples
Beans	Citrus	Barley
Broccoli	Maize	Carrots
Cauliflower	Oats	Celery
Clover	Radish	Cotton
Lettuce	Sugarbeet	Grapes
Peas	Tomato	Potatoes
Soya bean	Turnip	Peaches
Spinach	Wheat	Raspberry
		Rice
		Sorghum

Sources: Lucas and Knezek (1972); Shorrocks (1984).

Applying S has been found to decrease the Mo content of plants. The antagonistic effects of SO_4^{2-} on Mo content of plants have been suggested to occur primarily during the absorption process, with an antagonistic mechanism involved during translocation from roots to leaves (Gupta and Lipsett, 1981). Ryding (1982) observed that increasing the rate of Mo application increased Mo concentration in and uptake by plants, while both decreased with increasing rates of sulphate application.

Copper-molybdenum antagonism is well known, and toxicity arising from excess Mo in herbage is effectively prevented by applying Cu to the soil. Soils high in Fe_2O_3 are frequently deficient in Mo (Katyal and Randhawa, 1983).

MOLYBDENUM RESPONSES

Seed molybdenum content

Plants have very small Mo requirements. Seed Mo reserves, especially in large-seeded crops such as peas and maize, can make a significant contribution to the Mo status of the crop (Hagstrom and Berger, 1963). Tassel, anther and pollen development in maize seems to be sensitive to Mo deficiency (Agarwala et al, 1979).

Tanner (1978b) observed that the Mo concentration of maize grain was a controlling factor in the premature sprouting of grain on the cob, and that when the level of Mo fell below 0.05 ppm, the severity of sprouting was enhanced by heavy, late side-dressings of N fertilizer. The effect of Mo deficiency on premature sprouting is likely to operate through its limitation of nitrate reductase activity and the subsequent accumulation of inorganic nitrates which promote sprouting. This mechanism would explain the increased severity of sprouting with a decreasing number of grains per cob (Figure 2), as it is possible that the smaller grain 'sink' results in a greater concentration of nitrates in the remaining grains.

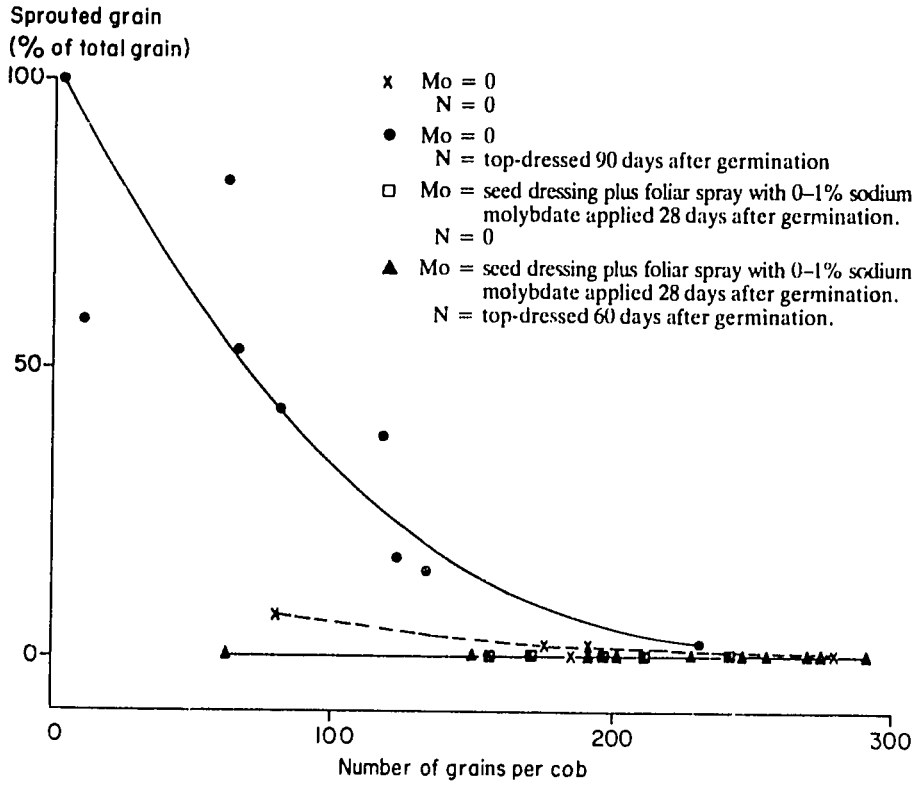
Tanner (1979) noticed that plant mass, plant stand and grain yield were significantly lower from R 200 maize seed containing 0.03 ppm Mo than from seed containing 0.50 ppm Mo, even though the seed had been dressed with sodium molybdate. On acid red clay loam soils in Zimbabwe, Mo deficiency symptoms developed in SR 52 maize grown from seed containing 0.13 ppm Mo or less. In contrast, none of the maize plants grown on granite sand soils which contain adequate Mo developed deficiency symptoms (Table 5).

The effect of seed Mo content on crop performance following seed dressing with sodium molybdate has been examined at two other sites in Zimbabwe (Tanner, 1982). All seed germinated satisfactorily and there were no Mo deficiency symptoms in the young plants. At one site, the mass of young SR 52 maize plants decreased from seed containing less than 0.04 ppm Mo even though seed dressing had been applied. Despite lower plant mass there was no significant relationship between seed Mo content and yield.

The development of deficiency symptoms in the maize plants was clearly related to the Mo concentration of the SR 52 seed. The largest percentage of plants showing distinct symptoms of Mo deficiency was produced from seed containing 0.01 ppm Mo, and the incidence of symptoms decreased as the Mo content of the seed increased. No seed containing more than 0.13 ppm Mo produced Mo-deficient plants (Tanner, 1982).

Commonly used sources of Mo are given in Table 6. Molybdenum deficiencies can be corrected by seed treatment and soil and

Figure 2. *Effect of Mo, N and number of grains per cob on percentage of sprouting in maize.*



Source: Tanner (1978b).

foliar application of Mo carriers. Molybdenum deficiency can also be rectified by liming acid soils.

Seed treatment

Molybdenum salts are applied to seed in a liquid or slurry form at a rate equivalent to 50 to 100 g Mo/ha (Katyal and Randhawa, 1983). Applying 28 g ammonium molybdate/ha as seed dressing increased kernel yield of groundnuts by more than 300 kg/ha in Senegal (Martin and Fourrier, 1965).

Pelleting seed with 0.2, 0.4 and 0.8 g sodium molybdate per 100 g seed plus inoculation with rhizobia was tested on groundnuts grown on an upland soil in Sierra Leone. Sodium molybdate at 0.2 g/100 g seed increased DM yield by 17.2%, N uptake by 38.5%, grain yield by 14.0% and protein content by 4.21% (Haque and Amara, 1978).

Rhodes and Nangju (1979) conducted two field experiments to evaluate the effectiveness of several pelleting materials in increasing the yields of cowpea and soya bean on an acid soil in Sierra Leone. Applied either alone or in combination with phosphate rock, Mo increased the growth and yield of cowpeas but had no effect on soya bean growth and yield, although it significantly increased the number of nodules per plant.

Haque and Bundu (1980) observed that inoculation and Mo application (0.4 g sodium molybdate/100 g seed) increased soya bean grain yield and protein content by 154% and 14.6% respectively over the control on an upland soil in Sierra Leone.

Rhodes and Kpaka (1982) found that applying Mo increased DM, pod weight and seed yield of cowpeas. Pelleting seed with nitromolybdenum at 0.4 g/100 g seed increased seed yield by 1.39 t/ha, or 21%, over the control (Table 7). This method of applying Mo should prove attractive to small farmers because it is simple, cheap, does not require spraying equipment and is less subject to the vagaries of rain and wind.

Graham and Morales (1974) reported on the influence of source and level of applied Mo on the survival of rhizobia in *Macroptilium atropurpureum* seed. Figure 3 shows that sodium molybdate cannot be used in contact with rhizobia. By contrast, both molybdic oxide and ammonium molybdate showed little evidence of toxicity. Even at the highest level of molybdic oxide applied (100 g Mo/6 kg seed) there was no significant decline in rhizobium numbers with storage. A slow decline in numbers surviving was evident with ammonium molybdate applied at this level, but this differed significantly from the molybdic oxide results only at the 20- and 30-day storage periods.

Table 5. *Effect of soil type and of seed Mo content on the percentage of SR 52 maize plants showing Mo deficiency symptoms.*

Site	Soil	Plants showing Mo deficiency (%)		
	Seed Mo (ppm):	<0.04	0.04–0.13	>0.13
Mt. Hampden	Red clay loam	33	17	0
Marandellas	Granite sand	0	0	0

Source: Tanner (1982).

Table 6. *Sources of molybdenum.*

Source	Formula	% Mo
Sodium molybdate	$NaMoO_4 2H_2O$	39
Ammonium molybdate	$(NH_4)_6Mo_7O_{24}4H_2O$	54
Molybdenum trioxide	MoO_3	66
Molybdenite	MoS_2	60
Molybdenum frits	—	2–3

Source: Murphy and Walsh (1972).

Foliar application

Molybdenum deficiencies in growing crops can be controlled using foliar sprays. A typical spray solution contains 0.1 to 0.3% of soluble Mo (Katyal and Randhawa, 1983). Lombin et al (1985) studied the effect of Mo (30 g ammonium molybdate/ha) sprayed 3 weeks after sowing on groundnut yields at Samaru, northern Nigeria, in a wet (1971) and a dry (1972) year (Table 8).

They found that in a dry year, Mo is more likely to increase the kernel yields of short-season groundnut varieties. In an earlier experiment, foliar application of Mo increased the kernel yield of groundnuts by 200 kg/ha (Kang and Osiname, 1972).

In Zimbabwe, foliar sprays of 100 g sodium molybdate/ha applied to maize 10 days after emergence eliminated Mo-deficiency symptoms (Tanner, 1982). However, applied 4 weeks after emergence, sprays of the same rate were ineffective. Tanner (1982) further observed that spraying 100 g sodium molybdate/ha on to a seed maize crop 10 days after emergence was sufficient to raise the seed Mo content above critical concentration (0.08 ppm Mo) on all but the most deficient soils.

Table 7. *Effects of Mo on cowpea performance.*

Treatment	Dry matter (g/plant)	Nodule weight (mg/plant)	Pod weight (t/ha)	Seed yield (t/ha)
No Mo	10.47a	144.0a	1.445a	1.15a
Mo sprayed[1]	13.09b	146.3b	1.519a	1.15a
Mo pelleted[2]	13.56b	179.0a	1.892b	1.39b
LSD (0.05)	2.08	49.3	0.22	0.18

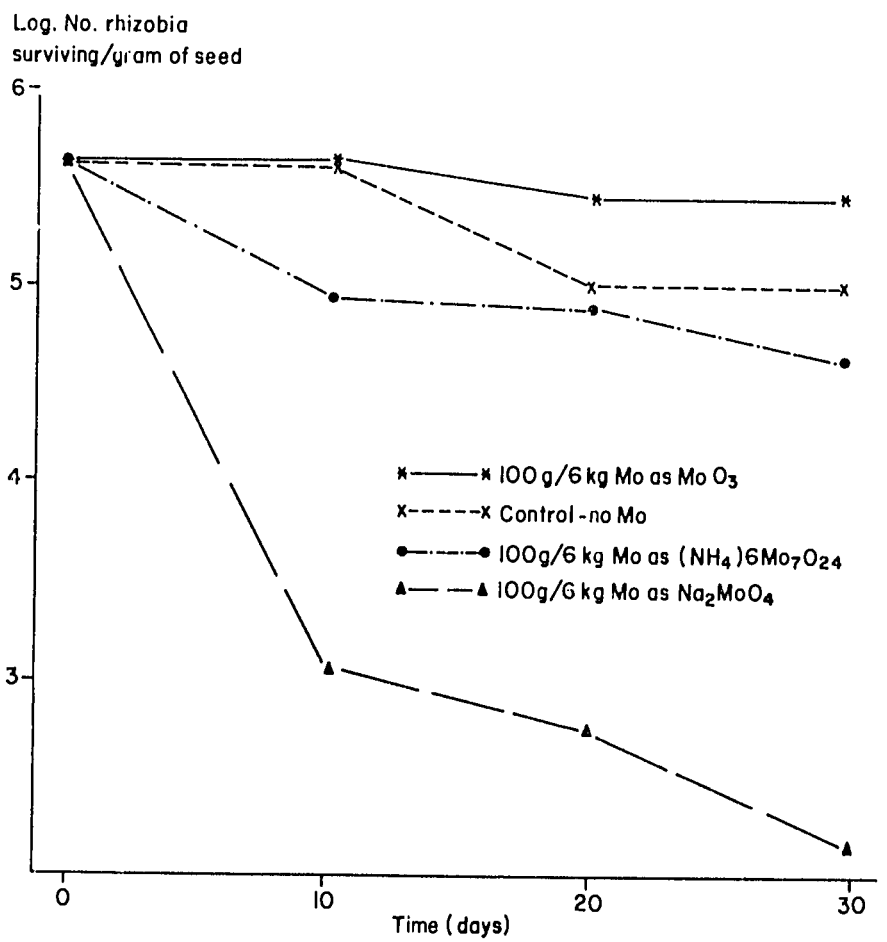
[1] 60 g Mo/ha as ammonium molybdate.

[2] 0.4 g nitromolybdenum/100 g seed.

Figures followed by the same letter are not significantly different at the 5% level.

Source: Rhodes and Kpaka (1982).

Figure 3. *Influence of form of Mo used on survival of rhizobia in Mo-treated seeds of Macroptilium atropurpureum.*



Source: Graham and Morales (1974).

Soil application

The optimum Mo dose varies among soils and crops. Generally, 70 to 200 g Mo/ha is sufficient for forage legumes and other field crops. Cauliflower may need up to 400 g Mo/ha. One application may produce residual effects on pasture and fodder plants for several years, but cauliflower may need Mo application every year (Katyal and Randhawa, 1983). In New Zealand and Australia, where pasture and arable crops are treated with Mo-enriched superphosphate giving 20 to 60 g Mo/ha, residual effects last for 1 to 15 years (Shorrocks, 1984).

Parish et al (1965) found that Mo applied to a low humic Latosol in Mauritius significantly improved sugar-cane growth. Molybdenum applications on the sandy aeolian soils in the West African semi-arid zone had beneficial effects on the growth, nodulation, N fixation and seed yield of groundnuts (Martin and Fourrier, 1965; Gillier, 1966).

In an experiment with cowpeas, positive growth response to Mo was observed on the acid Shante soil at Ogbomosho, which is typical of the sandy soils in the forest/savanna transition zone of Nigeria, and on the Adio soil at Ibadan. Applying 0.05 ppm Mo gave the largest response, with smaller responses occurring at rates up to 4 ppm Mo. However, Mo application decreased the weight and number of nodules as well as nitrogenase activity (IITA, 1975).

Maize appears to be relatively susceptible to Mo deficiency in acid soils. Greenhouse trials in Zimbabwe have shown Mo deficiency to be a major growth-limiting factor on a red clay-loam soil (Tanner, 1976). In field trials, applying Mo increased early maize growth on soils with pH between 4.4 and 4.8 (Tanner and Grant, 1977).

Liming

Applying lime may correct Mo deficiency on acid soils. In Kenya, Birch (1960) observed that Mo deficiency may be prevented by liming soils to pH 5.5. Rhodes and Nangju (1979) reported that the beneficial effect of Mo applications was comparable to or greater than that of liming with 3 t basic slag/ha.

Table 8. *Effect of Mo application on groundnut yield at Samaru, Nigeria, 1971 and 1972*[a].

Year	Variety	Plant part	Pod yield (kg/ha)		
			No Mo	With Mo	Difference
1971	$S.6_1$	kernel	1718	1894	+ 176
		haulm	2078	2892	+ 814
1972	$S.6_1$	kernel	1416	1293	- 123
		haulm	2992	3633	+ 614
1972	Spanish 205[b]	kernel	1893	2298	+ 405
	MK 374[b]	kernel	1922	2095	+ 173

[a] 1971 = wet year; 1972 = drought year.

[b] Spanish 205 and MK 374 varieties mature in 95 and 120 days respectively.

MOLYBDENUM–COPPER–SULPHUR INTER-RELATIONSHIPS IN LIVESTOCK

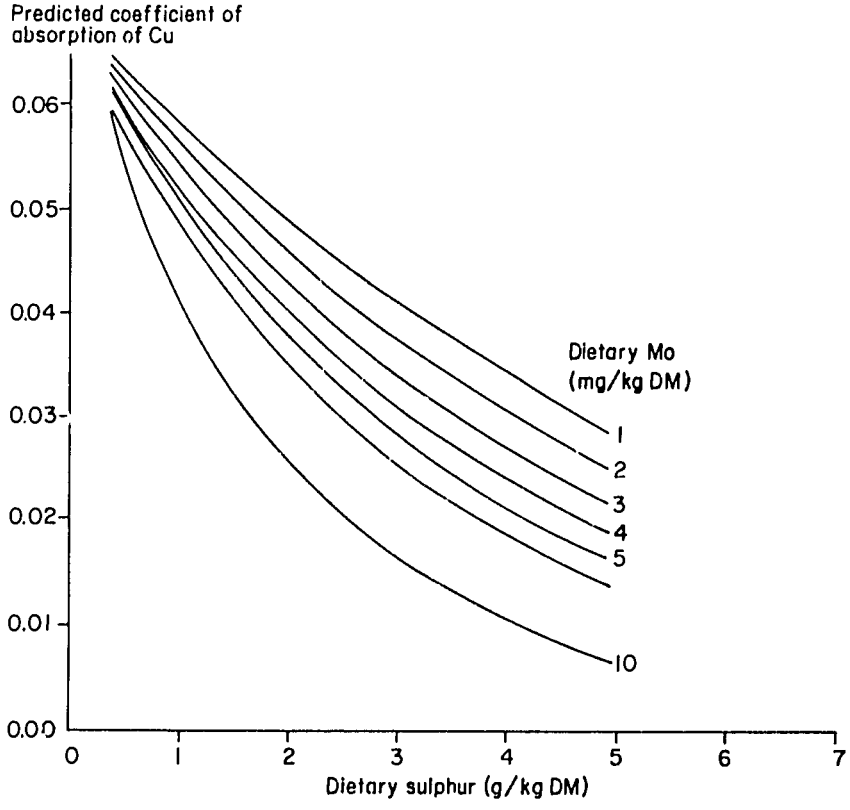
High concentrations of Mo (>10 to 20 ppm) seldom retard plant growth but are toxic to ruminants (Gupta and Lipsett, 1981). The dietary requirement for Mo in ruminants has not been determined accurately, since it is apparently very low. However, it has been accepted that a dietary concentration of 0.01 μg Mo/kg DM is adequate (ARC, 1980).

Mwakatundu (1977) found that plasma Mo concentrations in cattle ranged from 0.03 μg/100 ml at Morogoro (Tanzania) to 8.43 μg/100 ml at Egerton (Kenya). If the normal range of Mo in blood is taken to be 1 to 6 μg/100 ml, then animals at nine stations had sufficient Mo in their blood. Correlation coefficients between Mo concentrations in pasture and in plasma were highly significant ($r = 0.856$, $P<0.001$) for data obtained during the dry season.

Molybdenum toxicity (molybdenosis) operates mainly by inducing Cu deficiency, and affected animals respond to Cu supplements. The disease is known as *teart* in England and *peat scours* in New Zealand. Common symptoms include faded hair coats and profuse diarrhoea with foul-smelling faeces. Scouring of cattle and sheep may occur in restricted areas where the pastures contain subnormal levels of Cu and higher than normal levels of Mo, even though the Mo levels are well below those typical of teart herbage (Underwood, 1976).

Swayback, a Cu defficiency in lambs born of ewes that were Cu deficient during pregnancy, was found on pastures containing sufficient Cu, but having an imbalance of Cu, Mo and S (Todd, 1976). The fact that inorganic sulphate potentiates the adverse effect of Mo on the utilisation of Cu by sheep was first discovered by Dick (1953a; b): sulphate accelerates the clearance of Mo (Dick, 1956) and Mo influences the ruminal metabolism of sulphide (Mills, 1960; Gawthorne and Nader, 1976). Organic sulphur and inorganic sulphate share common metabolic fates (Anderson, 1956) and influence the output of soluble Cu from the rumen (Bird, 1970) by interacting with Mo (Suttle, 1975).

Figure 4. *Relationship for sheep of coefficient of absorption of dietary Cu to dietary content of total S and Mo.*



Sources: Suttle and McLauchlan (1976); ARC (1980).

Suttle and McLauchlan (1976) reported that S exerts an independent effect on the availability of Cu to sheep or cattle, and that the effect of S alone is greater than the S-dependent effect of Mo (Figure 4). Involving S in the interaction is preferable to the use of Cu:Mo ratios.

A totally different pathological entity that has been associated with diets and crops low in Mo is the high incidence of cancer of the oesophagus in parts of China and in the Transkei in South Africa. In both countries it is thought that the carcinogens are nitrosamines produced in the stomach from a diet rich in nitrites, but it is acknowledged that the connection between cancer and Mo is likely to be complicated by several other dietary and environmental factors (Shorrocks, 1984).

FUTURE OUTLOOK

In view of its role in N fixation, Mo could become more important in sub-Saharan Africa with the adoption of legumes in cropping systems. Studies on Mo toxicity in forages grown on soils with relatively prolonged wetness, high pH and under saline-sodic conditions merit particular attention.

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Some research and development implications for pastoral dairy production in Africa

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SUMMARY

THIS PAPER *examines the relative merits of milk versus meat production by African pastoralists and concludes that development of the pastoral dairy subsector is warranted on the following grounds. While there is rarely a surplus of live animals in pastoral economies, pastoral herds may produce more milk during seasons of high milk production than can either be consumed in the household or exchanged at profit. The second argument in favour of developing pastoral dairying is that many pastoralists are already engaged in a commercial exploitation of dairy produce, but are often constrained by lack of capital, inputs and suitable processing techniques. Lastly, since extensive commercial meat production requires more land per animal unit to achieve economic and energy outputs comparable to those achieved by dairying, the latter can offer a higher income to a greater number of people.*

INTRODUCTION

If we are to understand not only how pastoral peoples subsist but how they respond to market and climatic variations, the critical role of milk in pastoral systems must be appreciated. It is argued that while livestock development projects have typically sought to encourage pastoralists to increase only offtake of live animals, this emphasis has rarely been based on prior evaluations of the comparative efficiency, development potential and welfare benefits of dairying as opposed to meat production. Studies of pastoral dairying carried out by anthropologists, economists and nutritionists suggest that dairying makes a significant contribution to some pastoral groups' income and diet, and that the combined milk/meat production strategy pursued by these groups may yield greater output per unit of land than sole concentration on meat production. The conclusion is drawn that further multidisciplinary research on the biological and economic returns of milk versus meat production is required if livestock development planning is to be based on empirically sound grounds.

A fuller understanding of pastoral dairying is called for on several further grounds. Firstly, as pastoralists shift from dairy to meat production systems, there may be negative nutritional effects (Teitelbaum, 1977). Recently, a number of studies have demonstrated the nutritional contribution of milk to pastoralists (Swift, 1984; Wagenaar-Brouwer, 1984; White and Meadows, 1981).

Secondly, compared with sales of live animals marketing dairy produce may offer a more significant and reliable income source than is often realised. The bias towards research on animal offtake therefore needs to be redressed (Sandford, 1983, p. 200). The small but excellent sample of work on this topic in Africa does indeed indicate the importance of dairy income (Swift, 1979; Swift, 1984; Swift et al, 1982; for pastoral budgets, see White and Meadows, 1981; for agropastoral dairy incomes, see Hesse et al, 1984; Fulton and Toulmin, 1982; Waters-Bayer, 1985).

Thirdly, dairying and dairy product sales are often the responsibility of women, whose economic contribution to pastoral societies has generally been overlooked (Broch-Due et al, 1981; Horowitz, 1981; Oxby, 1983; Tavakolian, 1984). The now dated work of Dupire (1962; 1963) on the Fulani is still one of the best studies on women's participation in the dairying transactions between pastoralists and non-pastoralists.

Fourthly, the development of the traditional dairy sector as an alternative or complement to developing commercial meat production among pastoralists holds great potential for improving pastoral livelihoods and meeting the high demand for dairy products in Africa (Brumby and Gryseels, 1984; Mbogoh, 1984a,b). As Brumby and Gryseels have stressed, "In Africa only a minor fraction of milk production enters the official commercial sector" (1984, p.6), indicating that there is a highly active informal dairy sector towards which development efforts can be directed.

PASTORAL DAIRYING AND DEVELOPMENT ASSISTANCE

The importance of dairy production to the diet and economies of African pastoralists is well documented – notable early studies include Brown (1971), Dupire (1962; 1963), Hopen (1958) and Stenning (1959). Recent research in East Africa and in the Sahelian countries of West Africa has since provided quantified data on the contribution of dairy production, even among the

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so-called 'commercial' Maasai ranchers. Table 1 shows the important subsistence value of milk in terms of pastoral diets, which is hardly surprising given that pastoralists are, by definition, groups of people who live primarily from the products of their herds (Brown, 1971; Toulmin, 1983, p. 5). Much less well recognised is the market or exchange value of dairy produce, which, as Table 1 shows, may also be a significant component of pastoral income.

Development assistance to the dairy sector has been focused on the climatically more favourable highland areas of Africa, where higher milk yields are obtained and thus where the greatest potential for full-scale commercial dairying seems to exist (Jahnke, 1980; Mbogoh, 1984a). By contrast, projects concerned with the economic development of the drier, lowland areas where extensive pastoralism is practised have almost exclusively promoted commercial meat production (Sandford, 1983). Given the importance of dairy production in pastoral economies one should question the appropriateness of this emphasis.

Horowitz has pointed out, along with others (Behnke, 1983; Teitelbaum, 1977), that many development interventions in fact seek to convert a dairy-based economy to one where "the calf has the prime claim on milk .... the calf is a surrogate for the urban consumer of beef", i.e. calves are raised solely as beef-export animals rather than as animals sharing milk with the humans dependent on the herds (Horowitz, 1981, p. 86)[1].

Table 1. *Subsistence and commercial value of dairy products for Maasai ranchers in Kenya, the WoDaaBe in Niger and the Tuareg and Bella in Mali.*

Group	Value as % of total cash and subsistence income					
	Cattle sales and home consumption	Dairy sales	Milk consumed	Smallstock sales and slaughter	Other (wages etc.)	Total (%)
Individual Maasai ranchers[a]	34	11	14	10	31	100
Maasai group ranchers[a]	51	2	36	6	5	100
WoDaaBe[b]	45[b]	2	30	5 + 13[b]	7	100

Group	Value as % of total cash income			
	Livestock sales	Dairy sales	Other	Total (%)
Tuareg[c]	97	0	3	100
Bella[c]	37	38	25	100
Poor Tuareg and Bella	52	28	20	100

Group	Value as % of total kcal/year				
	Milk	Cereals	Meat	Other	Total (%)
Individual Maasai ranchers	51	22	11	16	100
Maasai group ranchers	63	11	7	19	100
WoDaaBe	40	53	--7[e]--		100
Rich Tuareg[d]	62	26	12	n.a.	100
Bella	49	36	15	n.a.	100

Sources and Notes:

[a] White and Meadows (1981).
Individual ranchers were wealthier, had larger herds (21 head/individual rancher compared with 12 head/group rancher) and had larger ranches than group ranchers (pp. 14–19).

[b] Swift (1984).
The figures in this table are computed from data given in Swift's study. Since home slaughters were not recorded in the study, the figure in column two refers to cattle sales only. The value of milk is taken to be equivalent to the barter value of milk for grain. Column five includes the value (13%) of sales and slaughters of other livestock.

[c] Swift et al (1982).
The Bella are a dependent group residing with the Tuareg. They own far fewer animals than their Tuareg patrons but receive from them milk cows on loan.

[d] Wagenaar-Brouwer (1984).
As in the above case, the sampled Tuareg group are wealthy livestock owners who have Bella dependents living with them and working for them.

[e] Includes meat and other products.

MILK VERSUS MEAT: THE DEVELOPMENT DEBATE

The consistent emphasis in livestock development projects on promoting beef production has usually been justified by project planners on one or more of the following grounds:

- Superior economic and biological efficiency of commercial beef production over what was viewed as 'subsistence' dairy production practised by pastoralists.
- Increasing the welfare and income of pastoralists.
- The removal of 'surplus' livestock being inefficiently 'stored' by pastoralists, which were exacerbating range degradation.
- Increasing meat offtake from the pastoral sector so as to meet national development objectives, specifically:
  - provision of meat to urban consumers,
  - reduction of meat imports, and

[1] This general thrust of livestock development projects is not confined to Africa; for example, the author of a study among pastoralists of Afghanistan remarks that a World Bank livestock project was seemingly based on the assumption that the pastoral economy of the Sheikhanzai was "sustained primarily by the breeding and marketing of live animals" whereas the author found that the "Sheikhanzai depended far more significantly on the production and exchange of dairy products" (Tavakolian, 1984, p. 444). Understandably the Sheikhanzai spurned the efforts to increase their sales of live animals planned to supply urban consumers.

- generating foreign exchange through meat exports.

Increasingly, each of these justifications has come under scrutiny, and there is now evidence that the first three points (upon which the viability of the fourth point rests) are based on faulty assumptions, as the following review indicates.

Superior economic and biological efficiency of meat production

Pastoral dairy-oriented systems have often been criticised as being both economically and biologically inefficient – the latter including ecologically unsound. One of the strongest early critiques is presented by Brown (1971), whose influential argument underlies many subsequent assertions concerning the advantages of meat production for pastoralists. Brown unequivocally claimed "the ecological undesirability of subsisting on milk in a habitat which is ecologically unsuited to milk production", referring (mostly) to East African pastoralists, and commented that "no rancher in his right senses would attempt to produce milk *commercially* in the type of semi-arid area in which nomadic pastoralists try to *subsist* on it" (p. 97, emphasis added). However, the flaw in this argument is to suggest equivalence between what is ecologically optimal and what is economically viable.

From this basic misconception stems much of the effort to turn African pastoralists into meat-producing ranchers. The valid comparison is whether pastoralists can produce meat only at similar levels of economic and biological efficiency as they currently produce both milk and meat, holding *all* other factors constant, such as the numbers of people and animals that can be supported per hectare, access to markets and inputs, opportunity cost of the land, and climate. Such comparisons, as Sandford (1983) has noted, are in fact rarely, if ever, carried out. One exception is a recent study of animal productivity per hectare on a Maasai group ranch in Kenya, which found that livestock sales and slaughter yielded on average 11 kg meat/ha/year, valued at KSh 50/ha/year. By comparison, milk produced on the same ranch for subsistence averaged nearly 15 kg/ha/year, valued at KSh 47/ha/year. Thus, in this mixed production system, the productivity of dairy operations was higher than that of meat production, while the economic values of each component were comparable (de Leeuw et al, 1984).

With regard to the comparative efficiencies of meat-only versus milk/meat offtake, one comparison of similar ecological areas indicates that the pastoral, mixed milk-meat system outstrips a beef ranching system (Cossins, 1985) if efficiency is measured in terms of gross energy output edible by humans. Using another measure of biological efficiency, that of conversion of feed energy by livestock, King (1983) points out that "there is nothing inefficient about dairy ranching versus beef [ranching]" since conversion of feed energy to milk is more efficient than that to beef (p. 75). The burden of proof lies with those who claim a superior level of biological efficiency from a meat-only production system.

Where it is economically to their advantage to do so, pastoralists have opted for greater commercial meat production, as for example in the cases of Somalia (Holtzman, 1982), Libya (Behnke, 1983) and Niger (Swift, 1984). With respect to biological efficiency, as the new generation of farming systems researchers often remind us, producers are generally much less concerned with it than are researchers; the highest and most secure economic returns are usually a producer's principal objective (Collinson, 1982).

In the absence of more case studies on the comparative efficiencies of milk versus meat production, one can nevertheless consider the evidence from general studies. Milk production systems worldwide can support on average about 2.5 times as many people per hectare as could be supported by beef or mutton production systems (Spedding, 1979, p. 130). The greater output per unit land area possible with milk production is due to the fact that humans can 'harvest' their food source – milk – at a lower point on the food chain than is the case with meat production. With respect to the efficiency of resource use (land, labour and capital) in generating calories, Spedding's worldwide review (1979, pp. 133–134) shows milk requiring marginally less labour but considerably less money to produce than meat. The efficiencies of product output per unit of feed, and of energy output per hectare, are likewise far higher for milk than beef production systems (generally in the order of between 2 and 3 to 1). Although, as the author cautions, these general relationships encompass a great variety of different production systems operating under widely differing conditions, they serve to emphasise the need for a more careful evaluation of the comparative efficiency between meat and milk production.

Pastoralists' welfare and income

The underlying assumption of governments and donor agencies which encourage increased commercial offtake of live animals is that higher rates of animal offtake will generate more income and greater welfare than *alternative* forms of livestock exploitation, such as dairying. Typically, however, such projects were planned and implemented without any assessment of current or potential economic returns to dairy production relative to live-animal sales. It was instead taken for granted that increased offtake of live animals was economically preferable to existing production systems and would therefore be welcomed by pastoralists.

To give one example, White and Meadows (1981) commented on a long-established ranching scheme among the Kenyan Maasai thus: "The major production objective of the [Ranch Development Programme initiated in the mid-1960s] was to increase the marketed offtake of beef, implying a move away from a predominantly subsistence milk production system..." (p.2). But evaluations carried out 20 years later show that project participants "continued to manage cattle for milk including milk sales rather than beef production" (pp. 2 and 3). An empirical study of both milk and beef parameters for these Maasai herds led White and Meadows to conclude that there was little scope for increasing beef production but that there was an unrealised potential for greater commercial milk production. This is an important conclusion for several reasons: firstly, the longevity of the Maasai ranching project and thus the time that the Maasai had had to respond in the manner intended and secondly, the implication that the objectives of the project were founded on an incorrect assessment of the value of dairy production to Maasai pastoralists.

Others working among African pastoralists have reached similar conclusions:

for example, Niamir (1982) observed in a study on the Dinka that one of the reasons that livestock production schemes aimed at increasing beef offtake "have been unsuccessful is precisely because they ignore the importance of milk, and the great reliance of the people [pastoralists] on live rather than dead cattle" (p. 120). Large-scale livestock projects have thus proceeded without having first measured dairy offtake rates, the value of subsistence and cash benefits from dairying, or the nutritional impact of decreasing the consumption of dairy products (for other examples, see HTS, 1974, 1976; Teitelbaum, 1977; Behnke, 1985a).

A recently completed, major baseline study of livestock in Niger did not include any measurements of milk offtake from pastoralists' herds in the research on animal production. The only data on dairying in this study were obtained by social rather than animal scientists (Swift, 1984). No study, to the author's knowledge, has yet compared the net income benefits to pastoralists of diverting milk to human consumption (as herd owners now do) versus allowing calves free access to milk (as is recommended by the proponents of meat production). Would the faster and greater weight gain by calves receiving all milk yield equal or greater economic returns than alternative uses of the milk under existing pastoral conditions? Yet without such comparative measures of income from dairying versus live-animal sales, project planners cannot claim that their efforts will *necessarily* increase the income and welfare of pastoralists. Once again, the burden of proof lies with those who assert this, while the responses of pastoralists exhorted to sell more animals and milk them less suggest strongly that they have reason not to share planners' assumptions.

There are several reasons why, under certain circumstances and for particular groups of pastoralists, the welfare and income returns from dairying surpass or equal those from selling animals. These reasons may be summarised as follows:

- The barter value of seasonally surplus milk traded for grain is calorically advantageous to pastoralists, saves them having to sell breeding animals to buy grain during unfavourable seasons, and provides them with a cheaper source of grain than purchasing at retail prices (Dahl and Hjort, 1976; Dupire, 1963; Swift, 1984; Toulmin, 1983).
- The use (consumption) value of milk to pastoralists is higher than its exchange (sale) value in terms of protein equivalents at retail prices. Thus, pastoralists would not be able to match the protein value of milk consumed if they sold the milk and attempted to replace the same amount of protein by purchasing foods with the money obtained from milk sales. There is nearly always a cost incurred by producers who replace home-produced food with food bought at retail prices. By the same token, the use value of milk will in general exceed the cash returns from selling live animals, in terms of protein replacement, except where interventions (e.g. food subsidies, famine relief etc.) distort the free play of market forces.
- The peak period of milk production (typically in the rainy season) provides milk for home consumption during the season when grain is often least available and most expensive i.e. during the so-called 'hunger months' (Swift, 1984; Teitelbaum, 1977; White and Meadows, 1981).
- The sharp drought-induced fluctuations in terms of trade between live animals and grain make total dependence on sales of live animals highly risky for pastoralists (Sutter, 1982; Swift, 1984). For example, in the Sahel drought in the early 1970s, the exchange rate for meat to grain fell to 1:1 by weight – grain having more calories than meat (Toulmin, 1983). Similar ratios were observed in the recent drought affecting Sudan (Behnke, 1985b). By contrast, the exchange ratios between dairy products and grain tend to be more stable, and to favour pastoralists, since milk production falls along with grain output under drought conditions. The cash value of dairy produce is therefore a more predictable source of income in the long term.
- Owners of small herds are often especially reliant on dairy income since they have too few disposable animals to sell in order to meet their cash needs, particularly to buy grain. This has been noted in the case of one group ranch among the Maasai; "where there is a market for milk, the poorer households will sell more than the richer households, both in absolute and relative terms" (White and Meadows, 1981, p. 109). Table 1 (given earlier) shows that poorer households among the Bella and Tuareg of Mali also rely heavily on dairy income, in contrast to wealthier households.
- The social position of pastoral women, who are often primarily responsible for dairy operations and providing family income through the sale of dairy products, may be threatened by a reduction of dairying in favour of animal sales. This can be considered a threat to social welfare, and is evidenced by the resistance frequently shown by women to projects which would reduce their dairy income (Broch-Due et al, 1981; Horowitz, 1981; Tavakolian, 1984; Waters-Bayer, 1985).

Lastly, but most importantly, livestock systems based on dairying can support more people per unit of land than can systems geared to meat production under similar technical conditions on African rangeland. In view of this relationship between land area and output, Toulmin (1983) has warned that "the gradual replacement of traditional pastoral production by meat-producing herds... has serious implications for rural employment and incomes. With the growth of modern production systems, substantial numbers of people will be displaced and will need to find alternative sources of income elsewhere" (p. 43).

The point suggested here is that since meat-production systems can support fewer people per land unit – although at higher returns per individual herd owner (provided markets, transport, price incentives and technical inputs are in place) – not all pastoralists using a given land area will be able to switch from dependence on dairying to meat production. Thus the income and welfare of some pastoralists will be endangered in order that other pastoralists can become fully commercial meat producers.

Removal of surplus livestock

Many livestock development projects in Africa have been based on the belief that animals in excess of subsistence needs were

being held by 'traditionally oriented' pastoralists for reasons of social prestige, ritual or as a 'store of wealth' (see for example Doran et al, 1979). Encouraging greater offtake of these supposedly surplus animals, it was argued, would improve the range, increase pastoralists' welfare and income (see above) and provide urban consumers or export markets with meat.

This view is now unsupportable, as the accumulated quantified data on herd structures have since revealed that pastoralists in general dispose of unproductive females and mature males that are surplus to draught, breeding and transport needs (for pastoralists in Niger, Mali and Sudan, see Swift, 1984, p. 104; for the Kenyan Maasai, see White and Meadows, 1981; for Somalia, see Box, 1971; for other East African groups, see Dyson-Hudson, 1974). Pastoral herds are mainly composed of breeding females, for the dual purposes of providing milk and males for sale. Any apparently 'surplus' mature males found in such herds are usually present for good reasons: Firstly, holding males until they reach mature weight brings a higher economic return at marginal extra cost than does selling all male calves when young; secondly, in drought-prone regions pastoralists need a reserve to sell in emergency; thirdly, owners may withhold saleable cattle until market prices are more attractive. The widely held conclusion of those who have actually studied the composition of pastoral herds is that animals will be slaughtered or sold when it is either economically advantageous or necessary.

IMPLICATIONS FOR LIVESTOCK DEVELOPMENT POLICY

Development-oriented research projects among African pastoralists have, in the past, failed in their search for a surplus of saleable animals which could supply outside markets (e.g. in South Darfur, Sudan – Martin Adams, pers. comm.). In pastoral economies there is rarely a surplus of live animals for sale (see for example HTS, 1974; Wilson and Clarke, 1976). However, what is less widely appreciated is that another quite real surplus often does exist. During seasons of high milk production, pastoral herds may produce more milk than herd owners can either consume or exchange at sufficiently attractive terms. Some milk is converted by the women into a semi-preserved form (such as butter oil or cheese) for later exchange or home consumption. Commercial exploitation of dairy produce is, however, often limited by the available processing techniques, by lack of capital or critical inputs, and by undeveloped marketing channels between producers and potential new consumers. It would thus appear that development of the pastoral dairy sector could supply producers with much-needed additional income, by taking advantage of an already existing surplus product from pastoral herds. That surplus is seasonally plentiful milk.

Another compelling reason for encouraging the commercialisation of dairying among pastoralists is that demand for dairy products is presently unmet in Africa. Mbogoh (1984b) has noted in a recent review of dairy development in sub-Saharan Africa that, throughout the region, demand for dairy products has long outstripped supply, with the deficit being made up by imports from Europe and North America. Due to agricultural subsidies in the industrialised West, dairy goods imported by African countries effectively undercut local producer prices which, by contrast, are not supported by African governments.

This has led to the situation in which a two-tiered dairy marketing system operates: a formal market offering producers low official prices reflecting the competitive import price, and informal marketing outlets "which tend to be low-cost operations ... in a position to pay higher prices to producers" (Mbogoh, 1984a, p. 8). The informal system handles the bulk of dairy processing and marketing in most African countries. The author further points out that attempts to promote the formal dairy sector have generally been unsuccessful due to low official producer prices and high capital costs of setting up and running modern dairies. Another problem may be the inefficient management of parastatal dairy plants.

Most milk producers prefer to sell through the 'traditional' system where they receive better prices for their products. Several case studies have drawn attention to this discrepancy; for example, women in the Kafr Al Bahr area in Egypt refuse to sell milk to local factories since they can obtain far greater returns by making and selling cheese independently (Zimmermann, 1982), while in northern Nigeria women were reported selling milk through the informal market at 5.5 times the price offered by a local commercial milk collection centre (Waters-Bayer, 1985). Similarly, local milk prices in a more arid pastoral area in Kenya were found to be 2.5 times higher than the official prices offered in an adjacent highland area with more rainfall (Lilljequist, 1983). In a survey carried out by ILCA, the ratio between traditional and official dairy prices was found to fluctuate between 1:1 and 3:1 in West and eastern Africa (Mbogoh, 1984b).

The point seems clear: given present official producer prices and capital costs, traditional dairy processing and marketing operations offer higher economic returns to producers than 'modern' dairies. The African continent is littered with modern dairies running at far below capacity, or which are simply defunct (Mbogoh, 1984b). Greater recognition is needed of how effectively traditional dairying operations currently meet demand, while further research is required on how this subsector can be assisted for the benefit of both the local producers and consumers.

A case against the commercialisation of pastoral dairying may be made on the grounds that an increase in the commercial value of milk would lead to a decrease in the amount of milk distributed within a pastoral society, either as in-kind payments for services or as gifts to poor dependants. Researchers, in particular anthropologists, who are familiar with the redistributive practices in pastoral societies may therefore argue that as milk acquires a cash value and is more often sold, the welfare of the poorer members of a pastoral society will be adversely affected.

There are several rejoinders to this objection. Firstly, throughout Africa pastoralists have become increasingly oriented towards production of live animals for sale to outside markets. Owners of larger herds, who have potentially the most surplus milk for local redistribution, have already shifted to commercial meat production, in the process deflecting more milk to calf growth (Behnke, 1985b; Solway 1980; White and Meadows, 1981). Consequently it is the owners of smaller herds, who are less able to shift to full-scale commercial meat production, who are most likely to benefit from dairying. Sec-

ondly, if milk becomes more valuable, payments for services in kind, in the form of giving milk cows to herders, for example, will be accordingly more valuable to the recipient. Thirdly, the substitution of cash for formerly in-kind transactions had typically followed upon the process of commercialisation. As live animals have acquired a commodity value in pastoral societies, exchanges formerly involving live animals (e.g. bridewealth, herding services, injury and homicide compensation, fines etc.) have gradually been replaced by cash payments (Toulmin, 1983). In the same manner, as milk increasingly becomes a commodity to be bought and sold, we can expect impacts on in-kind transactions similar to those that accompanied the shift in pastoral economies to commercial meat production.

To summarise the main points, while the development of dairying may well result in less milk being distributed within pastoral societies, a reduction in the availability of milk has already occurred due to the increased commodity value of live animals; dairying offers owners of smaller herds a means of increasing their income; and transactions previously involving the exchange of milk are likely to become monetarised rather than to simply attenuate.

CONCLUSION

The above discussion of the comparative benefits of commercial meat production versus commercial dairying among pastoralists leads to the conclusion that the development of the pastoral dairy subsector is warranted. Unlike the case with increasing offtake of live animals, there may well be a surplus of saleable milk in many pastoral economies; many pastoralists are already engaged in the commercial exploitation of milk, but are often limited by available techniques, inputs and capital. As with meat, there is an increasing demand for dairy produce within Africa. Lastly, given present levels of inputs and technology, extensive commercial meat production requires more land per animal unit to achieve economic and energy outputs comparable to those achieved with dairy production. The development of dairying can therefore potentially offer a higher income to a greater number of pastoralists than could be achieved with commercial meat production on the same area of land.

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Comparison of labour requirements for cropping maize on land previously used for *Stylosanthes* fodder banks and on adjacent fallows in the subhumid zone of Nigeria

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SUMMARY

THIS PAPER *examines the returns to labour from cropping fallowed land and land that has been used for Stylosanthes fodder banks in the subhumid zone of Nigeria. Contrary to the farmers' claims, the results of the study show that 'fodder bank soils' are easier to ridge than the adjacent natural fallows. However, due to the additional work needed to harvest the increased yield, cropping in fodder banks requires more labour. Although the technology has not yet been widely adopted, the trial with maize reported in this paper showed that incremental earnings of about 15% are possible, allowing for labour charges and assuming the extra yield was surplus to subsistence and had a lower marginal value.*

INTRODUCTION

ILCA has accumulated considerable evidence of the beneficial effects of *Stylosanthes* pastures on soils in the subhumid zone of Nigeria. These effects have been expressed in terms of crop yield i.e. returns on land area. However, land is not a limiting factor for cropping in the study area; labour availability during the peak periods of a growing season is the critical constraint.

Labour is the major input in subsistence farming and also largely determines the amount of land a farmer cultivates each year (Powell, 1986). In order to maximise the benefits from labour spent on a unit of land, the farmer usually adopts inter-cropping which exploits crops with different growing periods within the same season. With this technique, labour shortage is most critical at the time of land preparation, especially ridging which takes place during the peak period of labour demand (Ingawa, 1986). A delay in the onset of rains could aggravate this problem by shortening the period of land preparation before planting the first crop (Jones and Wild, 1975). The lack of labour needed to slash and burn land studded with bush after a natural fallow encourages farmers to continue cropping the same piece of land despite declining yields (Powell, 1986) and the need for rest periods between crop phases (Young and Wright, 1980). However, the reduction in grain yield caused by continuous cropping can in some instances be alleviated by the application of fertilizers.

In the subhumid zone of Nigeria, ILCA has been experimenting with fodder banks (concentrated fenced units of *Stylosanthes*, established and managed near the pastoralists' homesteads) to provide supplementary feeding for animals during the dry season. Mohamed-Saleem (1986) reported that maize grown in fodder banks of various ages produced higher grain yields than maize cultivated on previously cropped or natural fallow soils. This suggests that fodder banks could be used by agropastoralists for both fodder and grain production. The finding may also encourage arable farmers who have no livestock but are interested in the subsequent benefits of the technology to cropping to lease land to landless pastoralists for the establishment of fodder banks.

Farmers who are familiar with *Stylosanthes* experienced difficulties in tilling stylo soils, which implies the need for extra labour at the critical time of ridging. Informal interviews with the indigenes of Ganawuri (one of ILCA's case study areas in the subhumid zone of Nigeria) showed that this problem occurred with stylo that had been used for soil reclamation and allowed to become woody. In order to examine the extent of the problem, an experiment was undertaken to compare the labour inputs for cropping maize inside grazed fodder banks with those on adjacent natural fallows.

METHODS

The study was conducted at Abet (9°30' N, 8°25' E; 1300 mm rainfall between April and October) during the 1985 growing season. Two fodder banks of *Stylosanthes hamata* cv. Verano, established 3 and 4 years previously and grazed during all subsequent dry seasons, were identified. Four 15 m x 10 m plots were laid out inside each fodder bank. The plots were on sites in which the legume component was representative of that (50 to 60% stylo) found in other fodder banks in the subhumid zone of Nigeria. Comparable plots were demarcated immediately outside the fodder banks on fields that had been under natural grass fallow for at least 4 years.

All agricultural operations were carried out by the same hired labourers, who were allocated randomly among the replicated plots inside and outside the fodder banks. The operations included ridging twice, two fertilizer applications and two weeding operations followed by harvesting, which comprised plucking, dehusking and shel-

ling. The time taken to complete each task was recorded. Observations on labour input were also monitored by interviewing the workers.

In May 1985 the plots were ridged at 1-m intervals to a height of 30 cm. They were planted with the TZPB maize variety at a rate of 3 seeds per hole with a spacing of 0.25 m. After emergence, seedlings were thinned to one per hole. A uniform dose of 60 kg N/ha, 60 kg P/ha and 60 kg K/ha was applied as compound fertilizer (15:15:15) prior to planting and another dose of 60 kg N/ha was applied as urea 6 weeks later. Plots were weeded 5 and 8 weeks after sowing. At harvest, the cobs were plucked and then dehusked, dried and shelled to determine grain yield. The stalks were cut and dried at 60°C for 48 hours to determine the dry weight of crop residues. All data collected were analysed using analysis of variance.

RESULTS

Figure 1 (average of 2 sites) gives a breakdown of labour requirements by operation for cropping maize inside and outside the fodder banks. Cropping within fodder banks required 129 man-days/ha on average, compared with 110 days on natural fallows. Ridging 'fodder bank soil' required significantly less labour than did ridging soils under natural fallow, indicating that the latter was more difficult to till. This finding was supported by the workers taking part in the trial, who admitted that the 'natural fallow soil' was more difficult to ridge. More time was needed, however, to harvest maize grown within the fodder banks. This was because grain and crop residue yields on stylo plots were higher by 2 and 3 t/ha on average than those on natural fallow soils (Tables 1 and 2).

DISCUSSION

The study reported in this paper demonstrates that the labour requirement for ridging a 'fodder bank soil' was lower than that for ridging soils under natural fallow. The relative ease of tilling a soil previously under stylo was confirmed by the workers' perceptions of labour spent on ridging. Further evidence was provided by another study in the area in which Mohamed-Saleem et al (1986) found that soils that had been under stylo for 3 to 4 years had lower bulk densities (1.42 g/cm^3) than both fallows with similar grass species (1.61 g/cm^3) and repeatedly cropped soils (1.72 g/cm^3).

Table 1. *Average grain yields of maize grown on stylo and natural fallow soils, Abet, 1985.*

Location	Average grain yields (kg/ha)		Average of 2 sites
	Site 1	Site 2	
Inside fodder bank	4 785	4 533	4 659
Outside fodder bank	2 411	2 679	2 545
LSD (0.01)	452	335	

Figure 1. *Labour requirements for cropping maize on stylo and natural fallow soils.*

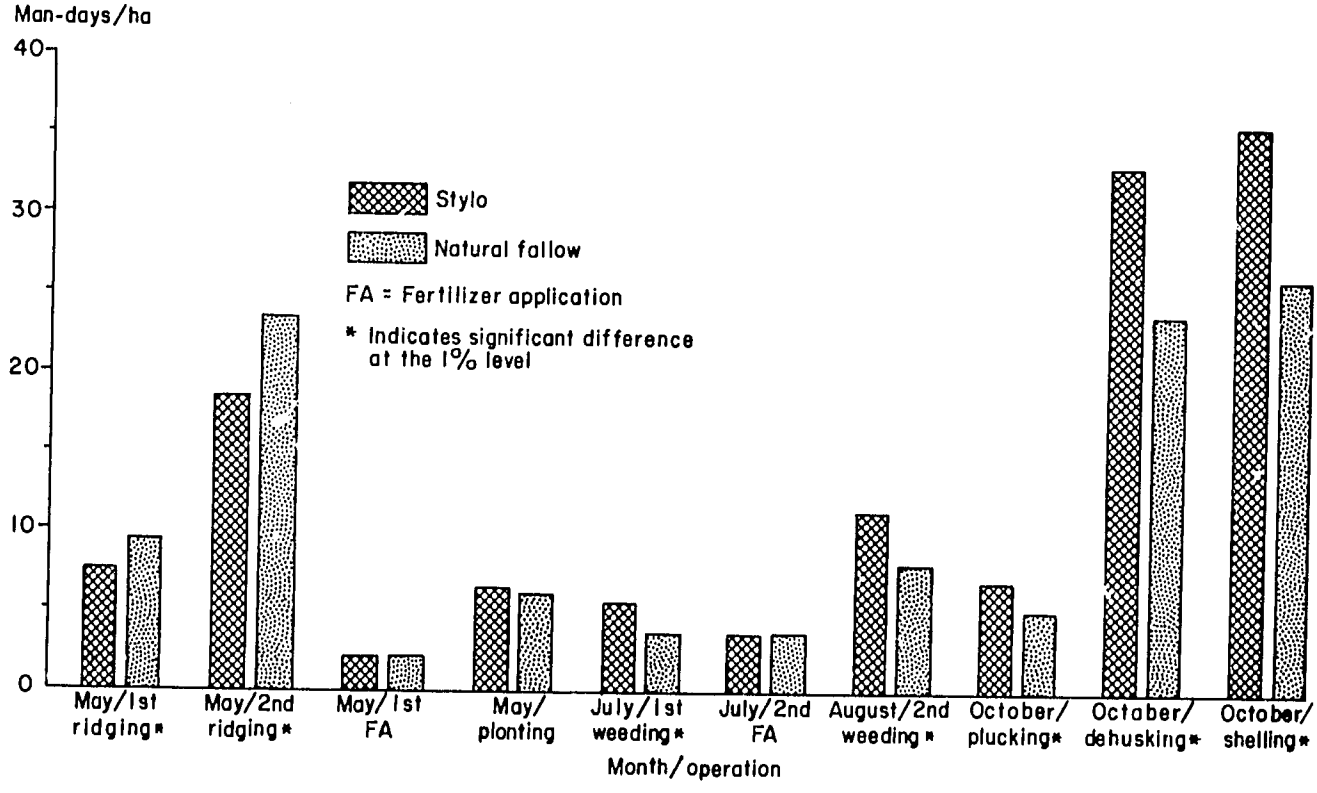

Table 2. *Average crop residue yields for maize grown on stylo and natural fallow soils, Abet, 1985.*

Location	Average crop residue yields (kg DM/ha) Site 1	Site 2	Average of 2 sites
Inside fodder bank	7 212	7 586	7 399
Outside fodder bank	4 018	4 523	4 271
LSD (0.01)	2 331	592	

Cropping causes a soil to lose its structure rapidly and to undergo compaction (Kowal and Kassam, 1978), which implies that continuously cropped soil will require more time to till.

More time was spent on other operations in the fodder banks than on fallows. This increased the total labour input on stylo sites by 19 man-days/ha, amounting to 129 man-days/ha as compared with a total of 110 man-days spent on cropping outside the fodder banks. Previous studies in the zone reported 103 man-days/ha for cropping maize on similar soils under similar farming conditions (Poate, 1980).

The extra labour required for weeding the cropped areas within the fodder banks was due to a greater weed growth resulting partly from the repeated emergence of stylo from a large seed reserve built up over the years. However, since the plots were weeded between July and August, which is a relatively less intense labour period (Ingawa, 1986), the labour input for this operation was not critical. Owing to the increased grain yield, the labour requirement for harvesting maize in the fodder banks was higher by 19 man-days/ha than that on natural fallows (Figure 1). During harvest demand for labour is high but assistance is available from women and children, who are not normally involved in ridging.

The observed increase in crop yields on 'fodder bank soils' confirms earlier findings in two other case study areas in the zone (Mohamed-Saleem, 1986), although the maize yield on stylo soils in this study was on average 1 tonne more at similar fertilizer rates. This could be attributed to a 200 mm higher rainfall and its better distribution in 1985 as compared with that in the previous 4 years. The crop yield differences inside and outside fodder banks are related to variations in the physical properties of the soils, which could have favoured higher water infiltration and nutrient retention by the post-*Stylosanthes* soil (Mohamed-Saleem et al, 1986).

The budgetary implications of increased labour use and crop yield are summarised in Table 3.

Cropping maize inside the fodder bank increased income by 124% over growing maize on fallow land. The potential benefit to agropastoralists can be derived by comparison with a budget for a typical herd of 40 cattle. According to Waters-Bayer (1986), a herd owner in Abet derives the following income from:

Sales of cattle	₦ 2080
Sales of dairy products	940
Total	₦ 3020

Powell and Taylor-Powell (1985) reported that pastoralists in Abet cultivate an average of 0.87 ha/household of which 0.24 ha is under maize. Hence the income from growing maize alone in a fodder bank would be ₦ 170.00.

Pending research on the yield responses of the other major cereal crops, an estimate of the potential incremental revenue for agropastoralists may be derived from the assumption that the total area under cereal crops is under maize i.e. 0.722 ha (83% of the average area cultivated by pastoralists). The total annual grain income from cropping a fallow is estimated at ₦ 411.00 (569.5 x 0.722), and the gross cattle and crop income would be ₦ 3431. The incremental revenue resulting from cropping a fodder bank would then be ₦ 511.4 (708.32 x 0.722), which is equivalent to 15% of the present annual income.

Data available so far suggest that fodder banks of highly productive legumes such as *Stylosanthes* spp. could be an alternative land use to a natural fallow in situations where high-quality fodder and the preservation of soil conditions are vital for increasing agropastoral outputs. Since labour is a major constraint, any operation that would increase labour requirement would not be readily acceptable to either farmers or pastoralists. Methods requiring low labour inputs for fodder bank establishment have already been demonstrated (Mohamed-Saleem et al, 1986). The results of the present study suggest that a cropping system with a forage legume interphase could greatly increase crop yields in addition to increasing livestock productivity which is the original objective of establishing fodder banks (Mani et al, 1986).

Table 3. *Budgets for growing maize on fallow land and in fodder banks, Abet, 1985.*

	Unit/ha	Unit cost/ha (₦)	Total cost/ha (₦)
Outside fodder bank			
Expenditure			
Labour	110 man-days	5.00	550.00
NPK	240 kg	0.21	50.40
Urea	125 kg	0.21	26.25
Total expenditure			626.65
Income			
Grain yield	2 545 kg	0.47[a]	1 196.15
Balance			569.50
Inside fodder bank[b]			
Expenditure			
Labour	19 man-days	5.00	95.00
NPK	Nil		
Urea	Nil		
Income			
Incremental grain yield	2 114 kg	0.38[c]	803.32
Incremental balance			708.32

[a] Retail price of maize in the region.
[b] Excludes benefits of improved cattle productivity.
[c] Wholesale price used to value surplus crop.

Sources: Ingawa (personal communication) for grain prices; fertilizer prices were obtained from the Farmers' Supplies Company, Kaduna State, Nigeria.

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Authors' style guide

POLICY AND AUDIENCE

The aims of the *ILCA Bulletin* are to present the results of livestock research by scientists at ILCA and at African national institutes, spread the knowledge of results in related disciplines, encourage national scientists to test new research techniques and technological innovations, and stimulate the adaptation to local conditions of applied research carried out by ILCA.

Thus the main audience of the *ILCA Bulletin* is made up by the following groups in sub-Saharan Africa: scientists working in livestock research and related fields, agricultural policy makers, administrators and development workers. The *ILCA Bulletin* is also distributed to scientists working outside Africa and to ILCA's donors.

MANUSCRIPTS

Articles may be submitted in English or French and should be from 3000 to 7000 words in length. The original, typed double-spaced on one side of the page only, and two photocopies should be sent to the Director of Training and Information, ILCA, P.O.Box 5689, Addis Ababa, Ethiopia. Papers submitted will be reviewed by two internal referees whose comments will be passed on to authors. If in the referees' opinion a paper is acceptable for publication, the author should send an amended draft to the Editor of the *Bulletin* for editing and publication.

FORMAT AND STYLE

Authors should give their names and initials, titles, programme or department, institute, postal address, and telex number if available. Articles should include a summary and, whenever possible, the following sections: introduction, materials and methods, results and discussion. The findings reported should be discussed in the broader context of livestock and agricultural production in Africa.

Data in figures and tables should be clearly presented and their salient points adequately discussed in text. In the case of figures please send original artwork with the final copy, not photocopies. Sources of figures and tables should be referenced. Abbreviations and symbols used in a figure or table should be explained in footnotes below. Good-quality black-and-white photographs are acceptable for publication. A full list of references must appear at the end of the paper, and authors may also include acknowledgements, disclaimers and/or a list of less common abbreviations and acronyms.

Metric units of measurement should be used (e.g. t/ha, kg, g, m and km). Where confusion is likely between l (one) and the abbreviation of litre (l), spell out the latter. The numbers one to nine should be written as words, except when used as measurements or units of time (e.g. 1 kg, 1 day, 1 hour but one cow). All other numbers should be written as numerals: note that numbers from 1000 to 9999 should be written without a comma or space, while from 10 000 onwards a space should be included. Articles will be edited to maintain a uniform style; substantial editorial changes will be referred to authors for approval.

Examples of common expressions and abbreviations

An increase of 6%; milk yield and consumption increased by 5% and 3% respectively; meat offtake decreased by 2 to 3%; km^2; m^3; 1300 h; 10°C; No.; 1.3 million; 1980/81 cropping season but ... Nigeria, 1980–82 (in table captions); 13 μg Mo; 1 kg N; Figure, *not* Fig.; use Jan, Feb, Mar, Apr, May, June, July, Aug, Sept, Oct, Nov, Dec in tables and figures if space is not sufficient; pp. 12–19, 365pp. (in references) but 'see page 3' (in text); P = probability ($P<0.05$, $P<0.01$ and $P<0.001$); LSD = least significant difference; SE ± = standard error; d.f. = degree(s) of freedom; MS = mean square; CV = coefficient of variation.

Distinguish between 'East African Shorthorned Zebu' (specific breed) and 'zebu' cattle (humped *Bos indicus* cattle); 'Boran' cows but 'Borana' people; 'West African Dwarf goat' (breed) but 'the dwarf goats of West Africa'; N'Dama cattle etc.; sp./spp. = species (sing./pl.); cv(s) = cultivar(s); var = variety.

REFERENCES

General: Do not italicise 'et al'; write 'ed.' for 'editor' and 'eds' for 'editors'; write date of publication without brackets; do not use fullstops after authors' initials; italicise titles of published books or reports; italicise titles of journals; use official abbreviations of journals; give volume, issue and page numbers of journal articles.

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LIST OF ABBREVIATIONS

Al	aluminium
ARC	Agricultural Research Council
B	boron
Bq	becquerel
Ci	curie
c.p.m.	counts per minute
Cs	cesium
CSO	Central Statistical Office (Zimbabwe)
ct	count
Cu	copper
d	disintegration
DM	dry matter
DMB	Dairy Marketing Board (Zimbabwe)
DMI	dry matter intake
d.p.m.	disintegrations per minute
ESCR	external standard channel's ratio
ESR	external standard ratio
Fe	iron
g	gram
Gy	grey (unit of radiation dose)
h	hour
H	hydrogen
ha	hectare
HDO/DOH	heavy/deuterated water
He	helium
HTO	tritiated water
IITA	International Institute of Tropical Agriculture (Nigeria)
IS	internal standard
K	potassium
keV	kilo electron volt
kg	kilogram
ln	natural logarithm
min	minute
ml	millilitre
Mn	manganese
Mo	molybdenum
N	nitrogen
₦	naira
OM	organic matter
P	phosphorus
ppm	parts per million
Ra	radium
rpm	revolutions per minute
S	sulphur
SCR	sample channel's ratio
SD	standard deviation
SE_b	standard error of the intercept
sec	second
S.I.	Système international
sp/spp	species
t	tonne
TBW	total body water
TCA	trichloroacetic acid
var	variety
Zn	zinc
Z$	Zimbabwe dollar