Journal of Agricultural Science, Cambridge (1997), **128**, 95–103. © 1997 *Cambridge University Press*

The energy expenditure of cattle and buffaloes walking and working in different soil conditions

J. T. DIJKMAN* AND P. R. LAWRENCE†

Centre for Tropical Veterinary Medicine, Easter Bush, Roslin, Midlothian, EH25 9RG, UK

(*Revised MS recieved 20 March 1996*)

SUMMARY

At the Centre for Tropical Veterinary Medicine, Scotland, during the summer months of 1987, two adult water buffaloes, two Brahman cattle and two Brahman × Friesian steers walked round a circular track on concrete or through 300 mm deep mud. Average walking speed (m/s) when unloaded, or average walking speed (m/s) when pulling 324 N, energy for walking (J/m/kg) and net mechanical efficiency (%) were 1·05 and 0·81 ($P < 0·01$), 1·03 and 0·80 ($P < 0·001$), 1·49 and 3·34 ($P < 0·001$) and 31·0 and 31·8 for concrete and mud respectively. Energy values were calculated from gaseous exchange measured with an open circuit system.

In Central Nigeria, from September 1991 to May 1992, the energy expenditure of eight Bunaji (White Fulani) bulls was monitored using portable oxygen measuring equipment (modified 'Oxylog') when walking, ploughing and harrowing on six soil surfaces ranging from hard, smooth earth to ploughed, waterlogged clay. Average walking speeds (m/s), pulling speeds (m/s) and energy cost of walking (J/m/kg) varied from 0·97 to 0·65, 0·55 to 0·47 and 1·47 to 8·58 respectively. Net mechanical efficiency averaged 31·4% and was unaffected by ground surface.

The energy cost of walking for the *Bos indicus* cattle on smooth ground (1·47 J/m/kg) in this trial was less than that previously reported for *Bos taurus* (1·80 J/m/kg) and the reported average value for cattle (*Bos indicus* and *Bos taurus*) on treadmills (2·09 J/m/kg). The implications for practical agriculture of the higher levels of energy expenditure for walking in muddy conditions are discussed.

INTRODUCTION

The energy cost of walking and working in cattle and buffaloes has been extensively researched (Hall & Brody 1934; Ribeiro *et al.* 1977; Lawrence & Richards 1980; Thomas & Pearson 1986; Lawrence & Stibbards 1990). Knowledge of the energy expenditure and quantification of the nutrient requirements of such animals, under as wide a range of conditions as possible, is necessary to develop more efficient ways of employing draught animals and of making the best use of feed resources available. The majority of these measurements were carried out while animals were walking and working on level, hard, dry surfaces of a treadmill or circular race. Values obtained under these conditions have subsequently been used in a factorial method to estimate the energy expenditure and the ensuing nutritional requirements of animals working in the field (Lawrence 1985, 1987; Mathers 1984; Graham 1985; Mathers *et al.* 1985). Animals working on farms, however, seldom operate under these conditions.

White & Yousef (1978) first reported on the extra energy expended on different terrain as the energy expenditure for walking in reindeer increased significantly (24%) in the change from dry to wet tundra. Energy consumption connected with walking can account for 40–60% of the total energy expenditure when draught animals are working on hard surfaces. An increase in the energy cost of walking under adverse conditions means that animals have less energy available to do useful work. In addition, it is likely that the use of the laboratory-based values in a factorial method can cause significant errors in the estimation of draught animal energy expenditure in the field.

This paper presents the results of two experiments set up to investigate the increase in energy expenditure for the various tasks that animals perform in the field associated with varying conditions underfoot. Initial

---

* Present address: Food and Agriculture Organization of the United Nations (FAO), Animal Production and Health Division, Room C-561, Viale delle Terme di Caracalla, 00100, Roma, Italy. To whom correspondence should be addressed.

† Present address: Institute for Animal Production, Hohenheim University (480), D-70593 Stuttgart, Germany.

investigations were carried out at the Centre for Tropical Veterinary Medicine (CTVM), Edinburgh, United Kingdom, during the summer months of 1987, where animals walked and worked in 300 mm deep mud in a circular track and these results were compared with the results obtained while the animals performed the same tasks when the track was not covered in mud. Additional experiments were done during the work of the International Livestock Research Institute (ILRI) on the introduction of animal traction into inland valleys in Kaduna, Nigeria, from September 1991 to May 1992. Seasonally inundated low-lying valleys or fadamas, which make up *c.* 7% of the total cultivable area of Africa, are an important feature of agriculture in the sub-humid zone of Africa (ILCA 1990). The valley bottoms are formed by the accumulation of fine soil particles. They are flat with a high clay or very fine sand content and inclined to be waterlogged. In contrast, the surrounding soil (known as the uplands), from which the fine particles are washed, is coarse and gritty, although still fairly fertile. In Nigeria, the valley bottoms are used almost exclusively by small-scale farmers for rice production and by peripatetic Fulani herdsmen as a source of winter grazing for their cattle. The uplands are used principally for the production of food crops such as maize and sorghum. Until recently, animal traction had been restricted to the Northern Sahelian zone of Nigeria, but with the decline of the tsetse challenge, ILRI commenced work on the introduction of animal traction into the sub-humid zone. During this work it became apparent that the consistency of the soil had a profound effect on the energy consumption of working animals. Hence the ILRI project-site offered an excellent place to investigate the issue.

The paper draws some general conclusions which should enable a more efficient and rational use of draught animals, provide basic information on food requirements and assist in the design of animal-drawn implements.

MATERIALS AND METHODS

Experiment 1

Animals and feeding

Six animals were used, two water buffaloes (*Bubalus bubalis*), two Brahman cattle (*Bos indicus*) and two Brahman × Friesian steers (Table 1). All animals had been trained from 1 year old and were familiar with the experimental procedures. During the experimental period they were fed a diet of medium quality hay calculated to provide maintenance energy requirements in two equal meals at 08.00 and 16.00 h daily.

Experimental procedure

Energy expenditure measurements were made while a single animal was in a circular race which consisted of two circular and concentric brick walls 610 mm high having radii of 3 and 5 m. When working, the animals pulled on a radial arm made of galvanized steel tube of 100 mm diameter and 4·5 m long. Where the arm passed over the inner wall, it was attached to a trolley made of angle iron which ran along the top of the wall on castors and included the hydraulic braking mechanism and a seat for the person in charge of the animals. At the centre of the race, the radial arm was attached via two pillow block bearings to a vertical spindle made of 75 mm diameter mild steel.

The gaseous exchange of the animals was measured using an open circuit gas analysis system (Lawrence *et al.* 1991). The animals under investigation wore a loose fitting face mask through which air was drawn at a constant rate chosen so that the maximum CO_2 concentration in the air leaving the mask approached but never exceeded 1·0%. Samples of inspired and mixed expired air were analysed for CO_2 increment and O_2 decrement and the results logged continuously into a modified personal computer. Energy consumption during any period was calculated using factors drawn up by Brouwer (1965) as:

O_2 consumption (l at standard temperature and pressure (STP)) × (16·16 + CO_2 consumption (l at STP)) × 5·09

No corrections were made to this formula to allow for methane production or the excretion of urinary nitrogen, as these factors are of little quantitative importance (Lawrence & Pearson 1985)

Air was drawn through the mask via a 5 cm diameter hose by a multistage centrifugal pump driven by an induction motor (Air Control Products, Chard, Somerset). The air flow rate was measured by a rotameter. Both pump and rotameter were attached to a horizontal wooden platform in the centre of the race which revolved with the main radial arm. A specially designed swivel was made to enable the electricity supply to reach the pump when the animals were walking round the race without tangling the cables. Another part of the same device allowed continuous removal of a sample of mixed expired air to the gas analysers, which were housed in a nearby laboratory.

While in the circular race, animals either stood still, walked round at a steady speed without a load, or walked at a steady speed while pulling against a hydraulically activated loading system. During the latter operation, the work done by the animals was measured using an ergometer (Lawrence & Pearson 1985), which also measured the distance travelled. The force required to move the trolley against the resistance produced by the hydraulic braking system varied little between trials. The average value for all trials (324 ± 10 N) was used in all subsequent calculations of work and power outputs.

Table 1. *Species, sex, ages and weights of animals used in Expt 1*

Species/breed	Sex	Age (years)	Liveweight range (kg)
Bubalus bubalis	male castrate	10	825–850
Bubalus bubalis	male castrate	9	770–800
Bos indicus	male castrate	9½	610–625
Bos indicus	female	3	370–400
Brahman × Friesian	male castrate	4½	625–675
Brahman × Friesian	male castrate	4½	645–695

When walking without a load, the animals were encouraged with verbal commands by someone walking inside the inner wall of the circular race slightly behind and to the left of the animal. When the animals pulled a load, the person was in approximately the same position relative to the animal but was seated on the trolley which contained the hydraulic braking system. The animals were thus continually encouraged to walk but were never beaten or goaded.

The respiratory exchange of each animal was measured for 20 min for each of the three types of activity and the results from the final 10 min used for subsequent calculations of energy expenditure. Inspection of the continuous records of gaseous exchange produced by the data-logging system showed that animals always reached a steady rate of energy expenditure after the first 10 min of a 20 min period when they were walking or pulling loads.

In any particular measuring session, an animal would stand, walk, pull and stand. The two standing values of energy consumption were averaged. Each animal was first tested for four sessions while walking on concrete. The circular race was then filled with mud to a depth of 300 mm for a further four sessions per animal. Finally the mud was removed and the four sessions on concrete were repeated.

No animal was used for more than two sessions in one day. The complete series of measurements was carried out over a period of 9 weeks.

Measurements were taken during the last 10 min of each part of each session as described above and the following data recorded: distance walked without load (m), distance walked with load (m) and the energy expended when standing still, walking and pulling (J). From these data were derived the energy cost of walking and the net mechanical efficiency of the animal defined as:

Energy cost of walking (Ew) (J/m/kg liveweight) =

$$\frac{\begin{pmatrix}\text{energy used while}\\ \text{walking (J)}\end{pmatrix}-\begin{pmatrix}\text{energy used while}\\ \text{standing still (J)}\end{pmatrix}}{\text{distance walked without load (m)} \times \text{liveweight (kg)}} \qquad (1)$$

The calculation of net efficiency was rather more complicated because the animals walked at different speeds when walking unloaded and pulling.

Table 2. *Species, ages and weights of animal pairs used in Expt 2*

Species/Breed	Age (years)	Liveweight range (kg)	Pair
Bos indicus	7	375–440	A
Bos indicus	7	385–440	
Bos indicus	5½	310–360	B
Bos indicus	5	380–430	
Bos indicus	4½	350–395	C
Bos indicus	4	305–355	
Bos indicus	6	385–430	
Bos indicus	6	335–380	D*

* Animals only used for 'walking upland'.

Net efficiency (%) =

$$\frac{\text{work done (J)} \times 100}{\begin{bmatrix}\text{energy used}\\ \text{pulling (J)}\end{bmatrix}-\begin{bmatrix}\text{energy used}\\ \text{standing (J)}\end{bmatrix}-\begin{bmatrix}\text{(Ew} \times \text{liveweight} \times \text{distance}\\ \text{travelled with load) (J)}\end{bmatrix}} \qquad (2)$$

(Lawrence & Stibbards 1990).

Statistical analysis of the results consisted of an analysis of variance using GENSTAT 5 (Genstat 5 Committee 1987), which compared walking speeds (loaded and unloaded), energy cost of walking and mechanical efficiency between individual animals, type of animal (buffalo, Brahman or Brahman cross) and surface (initial concrete, mud or final concrete). There were four replicates for each combination of animal and surface, giving a total of 72 sets of results.

Experiment 2

Animals and feeding

A total of eight Bunaji bulls (*Bos indicus*) were used in the initial upland walking trials of the Nigerian experiments. Subsequent measurements were carried out using six animals only, because one pair of bulls was not completely trained for cultivation work. All experimental determinations were made at Kufana village, 80 km south east of Kaduna in the sub-humid zone of Nigeria, from September 1991 to May 1992. The animals in Kufana were used throughout the year for cultivation, weeding and transportation for the ILRI project and had been in constant use over the past 3 years. The ages, weights and pairing of the animals are shown in Table 2.

The animals were fed 3 kg of concentrates each at 06.00 h (one hour before the start of the experiments) to ensure that they were mainly metabolizing carbohydrates during the experimental periods. Hence, the value of the respiratory quotient (RQ) probably

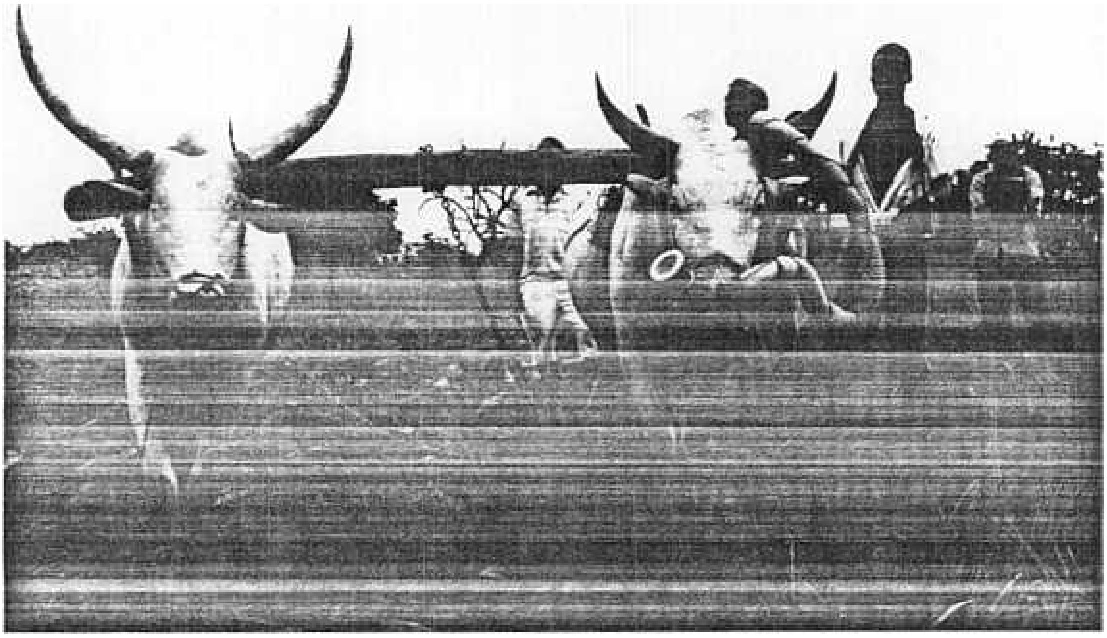

Fig. 1. Bunaji (White Fulani) bulls in Nigeria, showing an animal wearing the complete Oxylog instrumentation.

varied between 0·8 and 1·0 during the experimental period. The animals had continuous access to natural pasture, water and a salt lick. Ambient temperatures throughout the experimental period ranged between 22 and 31 °C with the relative humidity ranging between 0·30 and 0·85.

Experimental methods

Recent adaptation and validation of the Oxylog, which was originally designed for use with human beings (Humphrey & Wolff 1977), for use with draught animals (Lawrence *et al.* 1991; Dijkman 1993) has made it possible to measure accurately the O_2 consumption of animals working in the field. The Oxylog (PK Morgan Ltd, Kent, UK) uses a turbine flow meter mounted on the inlet side of the face mask. After each breath a small reciprocating pump takes samples of air entering and leaving the mask. The samples are passed into separate reservoirs containing a solid desiccant which give 'running average' O_2 concentrations which are measured using two polarographic O_2 electrodes linked differentially. The electronic system calculates and displays total O_2 consumption and total volume of inspired air at STP after making corrections for atmospheric temperature, pressure and humidity. Other functions allow the display of O_2 partial pressure difference between the inlet and outlet, and minute volumes of O_2 consumption and airflow.

Several adaptations were necessary in order to use the Oxylog for oxen. Firstly a mask was made to fit oxen which incorporated a saliva trap and allowed the animal to be guided either by a halter or by a nose ring. The seal consists of an annular cuff of 1 mm thick natural rubber which seals perfectly at a point just behind the animal's nose when the mask is pushed onto the face. The basic frame of the mask is made from 10 mm plywood and is of a geometrically simple shape. This means that new masks to fit animals of different sizes can be made quickly, easily and cheaply.

Secondly, larger versions of the turbine flow meter were made. It was found possible to make scaled up versions of this type of flow meter which gave good linear responses when calibrated using a reciprocating pump operated at different speeds to give a range of flow rates. The capacity of the inlet and outlet valves was increased simply by increasing their number from one to three and nesting them in a larger tube. Finally, the tube connecting the mask to the Oxylog was fitted with a bypass so that only a fraction of the air passed the sampling point (Fig. 1).

The animals were trained to wear the facemask, to carry the analysing and recording unit of the Oxylog and to the general experimental routine over a period of 4 weeks. This was essential to obtain high acceptance rates of the mask (in this case 100%) and to ensure that the animals breathed and worked normally while wearing the instruments. During the first 2 weeks of training, each animal wore a dummy mask for 30 min/day. Ballast equivalent to the weight of the Oxylog was placed in the Oxylog pouch on the girth strap to balance the counterweight. In the third and fourth week of training, animals were fitted with the complete Oxylog instrumentation and facemask. Each animal was trained for 45 min/day. Respiration rate/min, before and after the fitting of the facemask, was checked at the start of all experiments and no differences were found in any of the experimental animals.

During the experiments, animals walked and worked in pairs, as during the normal working routine of the farmers on the farm, and wore a neck yoke. The wearing of the Oxylog apparatus was rotated on a daily basis.

The measurements were made on three soils with different consistency: upland (firm, an animal does not sink into the soil), dry fadama (an animal sinks 50–250 mm into the soil), wet fadama (an animal sinks > 250 mm)

Both the modified Oxylog and ergometer (Lawrence & Pearson 1985) were used to monitor the performance of the animals enabling measurements, of O_2 consumption (l), ventilation volume (l) and, where applicable, distance travelled (m) and work done (J). Because the Oxylog displays are very small and difficult to read, a panel with two voltmeters, giving the readings for minute O_2 consumption and minute ventilation volume, and two digital counters, recording total O_2 consumption and total ventilation volume, was manufactured. This data viewing panel was connected to the recorder output on the Oxylog via a long cable, hence facilitating the manual 'data logging'.

Implements were connected to the middle of the yoke by a chain, with a load cell (Type 241 by Novatech Ltd, Hastings, UK, 0–3000 N) fitted between the implement and chain, so that all the force produced by the animals was channelled through the load cell. Hence the work done per animal was obtained by dividing the measured values by two. Distance averaged draught force (DADF) was calculated by dividing the work done by the distance walked.

All parameters were recorded every minute on the minute. During a typical experiment each animal went through the following routine:

(a) Rest	–	20 min
(b) Walk	–	20 min
(c) Work (i.e. pulling)	–	60 min (3 × 20 min)
(d) Walk	–	20 min
(e) Rest	–	20 min

Each activity was monitored for at least 20 min. This ensured that the animal reached a metabolic 'steady state' before the energy consumption associated with each particular activity was measured, and it allowed for the response time of the Oxylog. In well-fed animals, energy expenditure during each activity can be calculated by multiplying the average O_2 consumption (l/min) by 20·7 kJ (Brouwer 1965).

To enable continuous movement, the animals both walked and worked in large circles (minimum diameter 30 m). Animals were allowed to choose their own walking/working speed, but this was then maintained throughout the measurement period. Ew and the net mechanical efficiency of the animals were defined as in Eqns (1) and (2) respectively. The energy costs for both standing and walking were taken as the average of the first and final measurement.

Whilst ploughing, the lead animal walked on land which had already been ploughed and when harrowing both animals walked on ploughed land. This had a significant influence on the energy expended for walking. It was therefore decided to divide Ew into $Ew_{unploughed}$ and $Ew_{ploughed}$ for the three soil consistencies investigated. As in Expt 1, several separate measurements (in this case 3–5) for each animal for each activity were averaged to provide the single data points which were used in the analysis of variance of the results using GENSTAT 5 (Genstat 5 Committee 1987).

RESULTS

Experiment 1

Initial analysis showed that there was no significant difference for any of the measured parameters between the two individuals in each group of animals. Similarly, there was no significant difference between groups of animals, though there was a tendency for buffaloes to use more energy for walking on concrete than the other animals and for the Brahman cattle to walk faster than other animals, whether with or without a load (Table 3).

There were also differences in the performances of the animals on concrete before and after they worked in mud. During the second trial on concrete (concrete 2), the animals walked significantly faster when pulling a load (1·13 *v.* 0·92 m/s, $P < 0{\cdot}001$), than during the first trial on concrete (concrete 1). They also walked faster when unloaded and had a lower energy cost of walking during concrete 2 in comparison with concrete 1 (Table 3). The difference between the energy cost of walking for concrete 1 and concrete 2 (1·69 *v.* 1·29 J/m/kg, $P = 0{\cdot}073$), almost reached significance at $P < 0{\cdot}05$. The better performance of the animals during concrete 2 probably means that they were fitter after having already worked for 6 weeks during the first trial on concrete and in mud.

Table 3. *Walking speed when unloaded, walking speed when pulling an average load of 324 N, energy cost of walking and mechanical efficiency of draught animals on two different surfaces during Expt 1*

Surface	Animal	Walking speed (m/s)	Pulling speed (m/s)	Energy for walking (J/m/kg)	Mechanical efficiency (%)
Concrete	Buffalo	0·90	0·83	1·85	31·0
	Brahman	1·13	1·04	1·57	26·0
	Brahman x	0·94	0·90	1·65	31·9
Mud	Buffalo	0·78	0·77	3·56	36·1
	Brahman	0·95	0·92	2·89	29·1
	Brahman x	0·69	0·72	3·57	30·1
Concrete 2	Buffalo	1·01	1·06	1·56	28·1
	Brahman	1·23	1·26	1·27	35·5
	Brahman x	1·06	1·06	1·05	33·7
S.E. (9 D.F.)		0·07	0·07	0·19	2·8
Concrete 1	All animals	0·99	0·92	1·69	29·6
Mud	All animals	0·81	0·80	3·34	31·8
Concrete 2	All animals	1·10	1·13	1·29	32·4
S.E. (15 D.F.)		0·05	0·05	0·12	1·7

Table 4. *The energy cost and speed of walking of Bunaji bulls on ploughed or unploughed soils of different consistency in the sub-humid zone of Nigeria during Expt 2*

Soil	*n*	Walking speed (m/s)	Energy for walking (J/m/kg)
Unploughed upland	8	0·97	1·47
Ploughed upland	6	0·83	2·87
Unploughed dry fadama	6	0·87	1·76
Ploughed dry fadama	6	0·74	3·76
Unploughed wet fadama	6	0·80	3·30
Ploughed wet fadama	6	0·65	8·58
S.E., $n = 8$ (32 D.F.)		0·07	0·22
S.E., $n = 6$ (32 D.F.)		0·06	0·26

n = Number of animals.

Combination of the results for concrete 1 and 2 for all animals gives values of 1·05 and 1·03 for average walking and pulling speed (m/s), 1·49 for the energy cost of walking (J/m/kg) and 31·0 for the net mechanical efficiency (%). 300 mm deep mud significantly lowered walking ($P < 0\cdot01$) and pulling speed ($P < 0\cdot001$), in comparison to walking and pulling speed on concrete. In addition, the energy cost of walking in 300 mm deep mud showed a significant increase of 220% ($P < 0\cdot001$) from the energy cost of walking on concrete. The net mechanical efficiency at *c*. 30% was not affected.

Experiment 2

Pair A and B of the experimental animals (Table 2) were ready for experimental observations after 2 weeks of training. Pair C and D of the experimental animals, however, took substantially more time and patience to train. Nevertheless, at the end of the 4-week training period all experimental animals were fully accustomed and at ease with the experimental procedures and the wearing of the facemask.

Analysis showed that there was no significant difference for any of the measured parameters between the two individuals in each pairing. Similarly there was no significant difference between pairs, although pair C walked significantly faster during work on all soil consistencies ($P < 0\cdot05$).

There was a general tendency for Ew to increase significantly ($P < 0\cdot001$) in the change from unploughed to ploughed conditions underfoot. $Ew_{\text{ploughed upland}}$, which averaged 2·87 J/m/kg, meant an increase of 195% from $Ew_{\text{unploughed upland}}$. Similarly, $Ew_{\text{ploughed dry fadama}}$, which averaged 3·76 J/m/kg, showed an increase of 214% from $Ew_{\text{unploughed dry fadama}}$. In the case of $Ew_{\text{ploughed wet fadama}}$, which averaged 8·58 J/m/kg, the situation was even more extreme as this meant an increase of 260% in the change from unploughed to ploughed conditions (Table 4).

In conjunction with the general increase in the

Table 5. *Walking speed when pulling, mechanical efficiency and DADF of Bunaji bulls ploughing and harrowing on soils of different consistency in the sub-humid zone of Nigeria during Expt 2 (mean values for 6 animals)*

Activity	Pulling speed (m/s)	Mechanical efficiency (%)	DADF (N)
Ploughing upland	0·55	31·8	658
Harrowing upland	0·66	32·7	779
Ploughing dry fadama	0·53	30·2	1130
Harrowing dry fadama	0·51	32·3	1250
Ploughing wet fadama	0·46	30·5	1265
Harrowing wet fadama	0·47	31·1	1450
S.E. (30 D.F.)	0·04	1·4	63

DADF = distance average draught force.

energy expended for walking, walking speed showed a general decline with a reduction of the consistency of the soil. Walking speed decreased significantly ($P < 0·01$) in the change from unploughed to ploughed conditions on all soils investigated. The most significant decrease ($P < 0·001$) was observed on the wet fadama, where walking speed reduced by nearly 19% (Table 4).

The net mechanical efficiency for ploughing and harrowing was not significantly affected by the conditions underfoot and varied between 30·2 and 32·7% (Table 5). The DADF was significantly lower on all soils ($P < 0·001$ for upland and wet fadama; $P < 0·01$ for dry fadama) while animals were harrowing. Pulling speed, however, was only significantly affected ($P > 0·01$) on the upland (Table 5).

DISCUSSION

The differences in animal performance between the two trials on concrete in Expt 1, although not significantly different, emphasise the fact that it is essential in experiments of this kind to use animals which are well-trained not only in the sense of being easy to handle and tractable, but which have also attained a high and consistent level of physical fitness. In this study it was not possible to apply the usual statistical remedy to problems of this kind by applying the treatments at random, because filling the circular race required an estimated 20 tonnes of semi-liquid mud which could not be taken in and out easily.

The average energy cost of walking on concrete in Expt 1 (1·49 J/m/kg liveweight) was lower than the value obtained by Lawrence & Stibbards (1990), using the same measuring system, for animals walking on treadmills (2·09 J/m/kg for Brahman cattle and buffaloes) and slightly higher than the value for 'free' animals walking on beaten earth in Expt 2 (1·47 J/m/kg liveweight).

Comparison of these results with general formulae proposed by Tucker (1969) and Taylor *et al.* (1970) to predict the energy cost of locomotion, using, for example, an average liveweight of 387 kg for the animals in Expt 2, gives values of 3·3 J/m/kg and 1·0 J/m/kg respectively. As pointed out by Lawrence & Stibbards (1990), the measurements on which Tucker (1969) based his formula included the resting metabolic rate. This in conjunction with the fact that animals have, on average, a standing metabolic rate which is 26% higher on working days than on non-working days (Lawrence *et al.* 1989), lends more support to Tucker's (1969) higher estimate. King (1981) proposed a general formula for the energy expenditure of walking in Zebu cattle of 200 kg, fed at maintenance. He based his formula for the energy expenditure on the walking speed. Substitution of the average walking speed on unploughed upland (0·97 m/s) in Expt 2 gave a value of 1·15 J/m/kg, which was probably the best prediction of the three formulae considered.

The higher values obtained for Ew by Lawrence & Stibbards (1990) in the laboratory setting can be explained by the fact that during these types of experiment animals are forced to walk at a certain speed on a moving treadmill surface and probably spent energy balancing and slipping. In the present experiments, animals were allowed to choose their own walking speed, which was then maintained throughout the measurement period.

In recently published work, using a collection bag portable 'breath by breath' analyser, average walking values for German Simmental and Niger Zebu were respectively 1·84 J/m/kg and 1·03 J/m/kg (Clar 1991) and 1·75 J/m/kg and 1·45 J/m/kg (Rometsch 1995). Whereas the values obtained for Niger Zebu are in relative agreement with the current study, the average cost of locomotion observed in the German Simmentals was substantially higher. The Simmentals in the former studies were fed at 1·5 maintenance and were fat, whereas the Zebus were fed at maintenance and were thin. It is hypothesised that herein lies a possible explanation for the observed differences. The energy cost of carrying applied loads is greater than the energy costs of walking, especially when the load is placed on the middle of the back (Lawrence & Stibbards 1990). This would help explain the difference between fat and thin animals and also the apparent difference between *Bos indicus* and *Bos taurus*. *Bos indicus* carries its fat (when it has any) efficiently over its shoulders whereas *Bos taurus* carries it around the gut, which places strain on the spine and tends to impede its gait.

A crucial observation in Expt 2 was that the Ew on ploughed land doubled or more than doubled. These observations have nutritional implications for draught animals working on soils of differing consistencies. When animals were ploughing with a mouldboard plough, the lead animal walked on land which had already been ploughed and as a result spent between 20 and 25% more energy than its partner while doing the same job. Moreover, the walking speed went down as the energy expenditure for walking went up. These results were consistent with the results from Expt 1, where we observed a 124% increase in energy expenditure for walking when animals changed from walking on concrete to walking in 300 mm mud.

In the walking experiments, a decrease in soil consistency was linked to a decrease in walking speed and an increase in the energy expenditure for walking, but the situation when animals are ploughing or harrowing is slightly more complicated. Whereas the same trend of animals slowing down on the wetter soils can be observed, other factors which have an impact on the walking speed during work are the type of implement and the draught force needed for the specific cultivation.

Although animals will expend approximately the same amount of energy during a full working day (Lawrence 1985), whether they are doing 'light' or 'heavy' work, the energy expenditure per unit area and the actual cultivation time needed will be much higher. When animals are employed for part of the day only, the extra energy expenditure of the lead animal while ploughing has to be taken into account. When animals are harrowing, both animals will spend more energy for walking, and as a result less energy will be available during the working day for doing useful work.

The efficiency of doing work in Expt 2 was not influenced by the consistency of the soil. These results were again consistent with results in Expt 1. This, however, was expected as to obtain the efficiency of doing work the real energy cost for walking was subtracted from the extra energy expended during work. The fall in efficiency observed by Lawrence & Smith (1988), when animals were working on muddy soils in Costa Rica, was likely to be caused by an increase in Ew. Overall, the mechanical efficiencies measured were in the same range as the values reported for Brahman cattle, although substantially lower than the mechanical efficiency of buffaloes (Lawrence & Stibbards 1990). Mechanical efficiency reported by Agricultural Research Council (ARC 1980) and Thomas & Pearson (1986) were also 3–4% higher.

During ILRI's work, pilot trials have shown that it was possible to plough and harrow a large proportion of the fadama area in Kufana during the dry season using ox-drawn implements, whereas in all but a few places the soil was too hard for manual cultivation until the onset of the rains. Ox-drawn cultivation in the dry season had several advantages. Time was not a constraint and cultivation could be done more thoroughly. Working conditions were less stressful because it was dry and cool. The exposure of the soil to the winter sunshine killed many of the pests and weeds. Most important of all, the rice crop could be sown in the fadama as soon as sufficient rain had fallen and the farmers could devote all their time and energy to the cultivation of their upland food crops. The present results further demonstrate that it would make sense to cultivate the fadama soils in the dry season from an animal point of view. Not only are the animals likely to be in a better condition at that time of the year (Smith 1981), but also the soil is not too wet and, hence, Ew will be lower, which would leave more energy for doing useful work. Not only Ew increased as soils got further inundated with water, but also the DADF rose quite substantially. As a result more time, effort and energy was needed to cultivate a unit area. Although a system of dry season cultivation can be appropriate and more efficient from a scientific point of view, the implications of the actual implementation of such an idea will need careful consideration. For a start, fadamas constitute one of the main dry season grazing reservoirs for the cattle of the peripatetic Fulani herdsmen and the cultivation of these inland valleys during the dry period would restrict their use for grazing.

Our sincere thanks are due to I. Campbell and R. Archibald for their technical support at the Centre for Tropical Veterinary Medicine. Financial support from the International Livestock Research Institute during the work in Nigeria and the use of their facilities is gratefully acknowledged. Personal thanks are deserved by H. Fitzhugh and D. Little and all the ILRI Kaduna field staff.

REFERENCES

AGRICULTURAL RESEARCH COUNCIL (1980). *The Nutrient Requirements of Ruminant Livestock*. Farnham Royal, Slough: Commonwealth Agricultural Bureaux.

BROUWER, E. (1965). Report of the sub-committee on constants and factors. In *Proceedings of the Third Symposium on the Energy Metabolism of Farm Animals*.

EAAP Publication No. 11 (Ed. K. L. Blaxter), pp. 441–443. London: Academic Press.

Clar, U. (1991). *Entwicklung einer feldmethode zur messung des energie umsatzes bei zugtieren.* PhD thesis. University of Hohenheim.

Dijkman, J. T. (1993). *The measurement of draught ruminant energy expenditure in the field.* PhD thesis. Centre for Tropical Veterinary Medicine, University of Edinburgh.

Genstat 5 Committee (1987). *Genstat 5 Reference Manual.* Oxford: Clarendon Press.

Graham, N. McC. (1985). Relevance of the British metabolisable energy system in the feeding of draught animals. In *Draught Animal Power for Production* (Ed. J. W. Copland), pp. 96–98. An International Workshop on Draught Power for Production, Townsville, Australia. ACIAR Proceedings Series 10.

Hall, W. C. & Brody, S. (1934). The energy cost of horizontal walking in cattle and horses of various ages and body weights. University of Missouri Agricultural Experiment Station, *Research Bulletin* **208**.

Humphrey, S. J. E. & Wolff, H. S. (1977). The Oxylog. *Journal of Physiology* **267**, 12P.

International Livestock Centre for Africa (1990). *Annual Report and Programme Highlights.* Addis Ababa, Ethiopia: ILCA.

King, J. M. (1981). *Ungulate Water Turnover in Tropical Africa.* Monograph No. 6. Addis Ababa, Ethiopia: ILCA.

Lawrence, P. R. (1985). A review of the nutrient requirements of draught oxen. In *Draught Animal Power for Production* (Ed. J. W. Copland), pp. 59–63. An International Workshop on Draught Power for Production, Townsville, Australia. ACIAR Proceedings Series 10.

Lawrence, P. R. (1987). Nutrient requirements of working ruminants. In *An Introduction to Working Animals* (Ed. J. L. Falvey), pp. 61–79. Melbourne: MPW Australia.

Lawrence, P. R. & Pearson, R. A. (1985). Factors affecting the measurements of draught force, work output and power of oxen. *Journal of Agricultural Science, Cambridge* **105**, 703–714.

Lawrence, P. R. & Richards, J. I. (1980). The energy cost of walking in some tropical draught animals. *Animal Production* **30**, 455.

Lawrence, P. R. & Smith, A. J. (1988). A better beast of burden. *New Scientist* **1609**, 49–53.

Lawrence, P. R. & Stibbards, R. J. (1990). The energy costs of walking, carrying and pulling loads on flat surfaces by Brahman cattle and swamp buffalo. *Animal Production* **50**, 29–39.

Lawrence, P. R., Sosa, R. & Campbell, I. (1989). The underlying 'resting' energy consumption of oxen during work. *Proceedings of the Nutrition Society* **48**, 154A.

Lawrence, P. R., Pearson, R. A. & Dijkman, J. T. (1991). Techniques for measuring whole body energy expenditure of working animals: a critical review. In *Isotope and Related Techniques in Animal Production and Health*, pp. 211–232. Vienna: International Atomic Energy Agency.

Mathers, J. C. (1984). Nutrition of draught animals. In *Animal Energy in Agriculture in Africa and Asia*, pp. 60–66. FAO Expert Consultation on Appropiate Use of Animal Energy in Agriculture in Africa and Asia, 15–19 Nov. 1982. FAO Animal Production and Health Paper 42. Rome: FAO.

Mathers, J. C., Pearson, R. A., Sneddon, J. C., Matthewman, R. W. & Smith, A. J. (1985). The use of draught cows in agricultural systems with particular reference to their nutritional needs. In *Milk Production in Developing Countries* (Ed. A. J. Smith), pp. 476–496. Edinburgh: Edinburgh University Press.

Ribeiro, J. M. de C. R., Brockway, J. M. & Webster, A. J. F. (1977). A note on the energy cost of walking in cattle. *Animal Production* **25**, 107–110.

Rometsch, M. (1995). *Energieumsatz und herzfrequenz von zugochsen.* PhD thesis, University of Hohenheim.

Smith, A. J. (1981). Role of draught animals in agricultural systems in developing countries. In *Vegetable Productivity: the Role of Vegetables in Feeding People and Livestock* (Ed. C. R. W. Spedding), pp. 247–262. London: Macmillan.

Taylor, C. R., Schmidt-Nielsen, K. & Raab, J. L. (1970). Scaling of energetic cost of running to body size in mammals. *American Journal of Physiology* **219**, 1104–1107.

Thomas, C. K. & Pearson, R. A. (1986). Effects of ambient temperature and of head cooling on energy expenditure, food intake and heat tolerance of Brahman and Brahman × Friesian cattle working on treadmills. *Animal Production* **43**, 83–90.

Tucker, V. A. (1969). Energetic cost of locomotion in animals. *Comparative Biochemistry and Physiology* **34**, 841–846.

White, R. G. & Yousef, M. K. (1978). Energy expenditure in reindeer walking on roads and on tundra. *Canadian Journal of Zoology* **56**, 215–223.