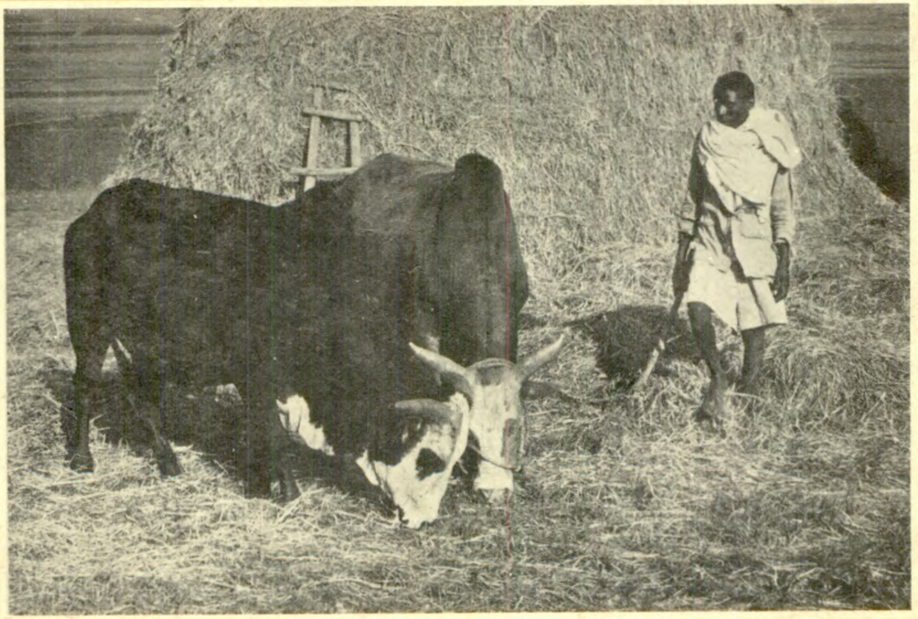
PLANT BREEDING AND THE NUTRITIVE VALUE OF CROP RESIDUES

PROCEEDINGS OF A WORKSHOP
HELD AT ILCA, ADDIS ABABA, ETHIOPIA
7–10 DECEMBER 1987



JUNE 1988

INTERNATIONAL LIVESTOCK CENTRE FOR AFRICA
P.O. BOX 5689, ADDIS ABABA, ETHIOPIA

Cover: *Zebu oxen eating barley straw in the Ethiopian highlands.*

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ABSTRACT

This document contains 12 papers on topics related to the use of crop residues as livestock feed in smallholder crop/livestock farming systems, and the role of plant breeding in maintaining or improving their nutritive value. Workshop sessions covered the role of crop residues as feed resources in smallholder crop/livestock farming systems (3 papers); factors limiting the nutritive value of crop residues (3 papers); the effect of genotype and environment on the nutritive value of crop residues (4 papers); and perspectives and implications for crop improvement programmes. A fifth section presents reports of working groups on aspects relating to the main workshop sessions, and makes specific recommendations on areas needing further research and modes for collaboration between crop and livestock research programmes.

KEY WORDS

/Crop residues//Animal nutrition//Animal feeding/ /Plant breeding//Smallscale farming//Mixed farming//Nutritive value//Genotype//Environment/ /Research/

RESUME

Le présent document contient 12 communications présentées lors d'un atelier consacré à l'utilisation des résidus de récolte comme aliments du bétail dans les systèmes de production mixte, et sur les possibilités d'amélioration de la valeur nutritive de ces résidus par la sélection. Les sessions de cet atelier ont porté sur le rôle des résidus de récolte en tant que ressource fourragère dans les systèmes mixtes (3 communications); sur les facteurs limitant leur valeur nutritive (3 communications); sur l'influence du génotype et du milieu sur cette valeur nutritive (4 communications); et sur l'intégration des critères retenus aux programmes d'amélioration des cultures. Les rapports élaborés par les différents groupes de travail sont présentés dans la cinquième partie de ce document, ainsi que des recommandations sur les axes de recherche prioritaires et sur les modalités de collaboration entre agronomes et zootechniciens.

MOTS CLES

/Résidus de récolte//Nutrition animale//Alimentation du bétail//Sélection végétale//Petite exploitation/ /Exploitation mixte//Valeur nutritive//Génotype/ /Environnement//Recherche

PREFACE

The objectives of this workshop were to bring together scientists involved in research on crop improvement, ruminant nutrition, feed chemistry and animal production to:

- o discuss and assess the effects of current trends in plant breeding on the nutritive value of crop residues;

- o consider the economic benefits of high-yielding varieties (both grain and residue) to smallholder crop/livestock farming systems; and

- o identify parameters that need to be monitored in order to maintain high nutritive value of crop residues.

The workshop was organised into five sessions, and these form the major divisions of the proceedings. Session 1 set the stage for our deliberations by stressing the importance of crop residues as feed resources in smallholder crop/livestock farming systems. Session 2 highlighted the problems of using crop residues as feeds by combining presentations on basic problems of feed chemistry and ruminant nutrition. These two sessions, presented during the first day of the workshop, provided the background material for discussions during the next three sessions.

Session 3 presented four case studies on the effects of genotype and environment on the nutritive value of crop residues. Sessions 2 and 3 were presented by feed chemists and ruminant nutritionists. The workshop organisers sincerely appreciated the patience and enthusiasm shown by the scientists associated with crop improvement programmes during these sessions and the constructive dialogue that developed between scientists from disciplines which, for the most part, are separated by institutional boundaries.

Session 4 was intended to present the perspectives and implications for crop improvement programmes primarily from the viewpoint of the plant breeder. However, one problem encountered was to find plant breeders who have participated in this type of research, and only one paper was presented by a plant breeder.

Session 5, the concluding session, was also designed to obtain the perspectives of crop scientists, through discussion with scientists from other disciplines, on future prospects for plant breeding to maintain or improve the nutritive value of crop residues. These discussions led to the recommendations made in the final section of the proceedings. The workshop organisers wish to express their gratitude to all the participants for their active and constructive involvement in this session.

Finally, the organisers wish to thank ILCA and all the other institutions that provided funding for the participants. Each CGIAR centre funded its scientists. The Technical Centre for Agricultural and Rural Co-operation, ACP-EEC Lome Convention, provided funds for the participation of several scientists from national programmes. Participants were also funded by the Overseas Development and Natural Resources Institute and the Institute of Grassland and Animal Production, UK.

We hope that the proceedings will be useful to researchers interested in crop/livestock interactions and the importance of crop residues as feed resources in smallholder farming systems.

Jess Reed
Brian Capper
Paul Neate

April 1988

CONTENTS

SESSION 1

THE ROLE OF CROP RESIDUES AS FEED RESOURCES IN SMALLHOLDER CROP/LIVESTOCK FARMING SYSTEMS

IMPORTANCE OF CROP RESIDUES FOR FEEDING LIVESTOCK IN SMALLHOLDER FARMING SYSTEMS

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INTRODUCTION

In the tropics (latitudes 30°N to 30°S), 40 to 80% of the livestock are associated with mixed crop-livestock farming systems, e.g. Africa 60% (Brumby, 1987, World Bank, 1987). Because of this close relationship between crop and livestock production, animal scientists are highly concerned by plant breeders' efforts to change the distribution of plant nutrients to the point that the nutritive value of the crop residues becomes too low for animals to obtain even their maintenance requirements. This reduction in feeding value of grain crop residues has often resulted in low adoption of new varieties by smallholders.

Agronomists and livestock scientists both aim at improving the welfare of farmers. However, efforts to improve farm productivity of crops and livestock have often been less successful than anticipated. Even so, African countries in which crop production has increased considerably during the last decade had a corresponding increase in livestock numbers (Brumby, 1987). When projecting farm output the interdependence of crops and livestock must be taken into consideration. On almost all small farms there is a strong interaction between cropping systems and livestock, and this results in poor adoption by farmers of either agronomic or livestock interventions developed in isolation (Hart and McDowell, 1985). This presentation focuses on crop-livestock interactions, which are important to both agronomists and animal scientists.

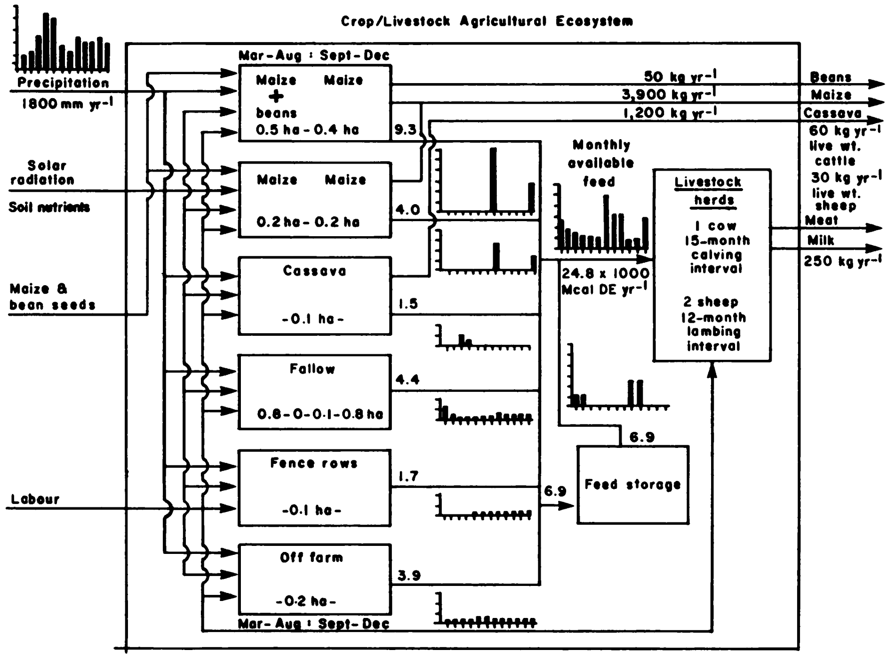
CROP-LIVESTOCK SYSTEMS

There have been a number of efforts to identify and describe farming systems in warm-climate regions based largely on geography (political and physical), climate, cropping pattern and animal output. Seldom has there been focus on crop-livestock relations.

Emphasising crop-livestock relations, McDowell and Hildebrand (1980) identified prevailing systems on small, mixed farms in Africa, Asia and Latin America. Ten major systems were identified in Asia: with the exception of swidden (slash-and-burn) farming, crop residues and byproducts from human food processing provided 30 to 90% of livestock feed. Africa has 10 major systems with 22 subsystems: dependence of livestock on crop residues was high in all 22 subsystems. In Latin America, four major systems were identified: in all except one, (commercial cattle ranching) crop residues provided 30 to 90% of livestock feed. Nearly all systems on the three continents also depended on grazing from fallowed crop lands.

The close interdependence of crops and livestock in smallholder systems in the highlands of Kenya is shown in Figure 1. Average farm size is approximately 1 ha and more than 85% of farms have livestock, usually two or more species. The interdependence of crops and livestock is primarily through dependence of animals on crop residues

Figure 1. *A crop/livestock agricultural ecosystem common in 1 ha farms in the western province of Kenya. Flows between crops and livestock are in 1000 Mcal of digestible energy (DE). Histograms show monthly distributions.*



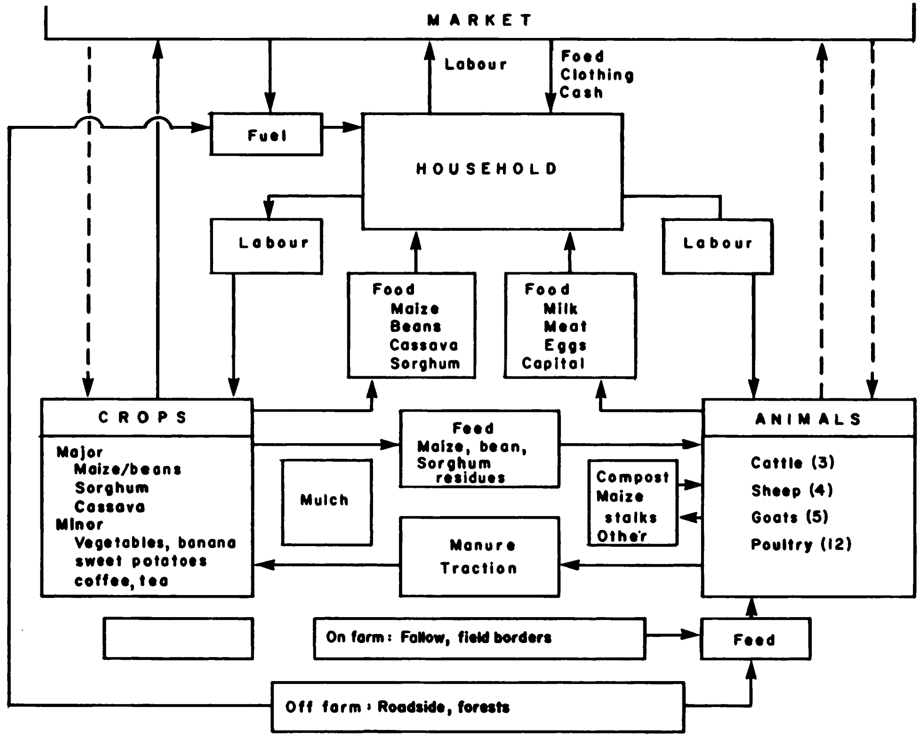
Source: Hart and McDowell (1985)

for feed. Farmers manage individual cropping patterns (intercropped maize and beans, double cropped maize and cassava) to provide food and feed. Each crop contributes feed during various months (histogram, Figure 1). Neither crop nor livestock productivity can be increased without due consideration of the interaction between crops and livestock.

Farms depicted in Figure 1 may on occasion hire animal traction for land preparation, but most cropping is by hand. Farmers keep, on average, one cow, two sheep and several poultry using farm and external feed sources, such as grazing or material cut from roadsides and forest. Maize stover is the most important feed. Farmers in this area have made little use of improved maize varieties because their stover yield is low unless fertilizer is applied and the indigestible neutral detergent fibre fraction (INDF) in their stover is higher whether with or without fertilizer.

Although crop and animal production can be strongly interdependent, the factors that can influence farmers' decision-making are often more complex (Figure 2). Sands (1983) made an in-depth study of the contributions of animals on 80 farms in two districts of western Kenya (mean size 1.03 ha). Using a two-dimensional model (household-market and household-farm), as proposed by McDowell and Hildebrand (1980), two major sub-systems requiring labour and capital were characterised. The solid lines from the crop subsystem to the animal subsystem show high dependence of animals on crop residues and strong dependence of cropping on animals for power in land preparation and fertilizer from manure dropped on fallow land while grazing or manure collected from night

Figure 2. *Model of typical low resource farms in the highlands of western Kenya with crop and animal sub-systems.*



Source: McDowell (1985)

holding areas for composting with inedible crop residues.

The solid line between crops and the market indicates the importance of crop sales: grain sales provide over 20% of household income. The broken line from market to crops shows low dependence on the market for inputs of seed, fertilizer or pesticides. Although annual income from sale of animals or their products equals or exceeds income from crops, the animal subsystem has an unpredictable relation to the market, i.e., sales of milk or animals are erratic. As with crops, purchases of inputs, e.g. animals, feeds or veterinary services, are sporadic. This implies that animals are kept largely for services to cropping, storage of capital, some household food and income and to provide for emergency needs: nevertheless, they are essential to the total farm operation.

For systems portrayed in Figure 2, interventions in either the crop or livestock subsystem would need to be approached cautiously for farmer acceptance and to avoid an unacceptable imbalance, such as less fodder or need of more feed for a crossbred cow. The solid arrow from household to market shows significant off-farm employment, hence availability of labour could be a constraint to adoption of new practices in either subsystem. Obviously, cash flow to the farms is low; therefore, inputs requiring capital will have low acceptance for either subsystem.

It is clear that agronomists and animal scientists must work together to increase production from these small mixed farms and that the extent of interactions between crops and livestock must be determined before interventions can be developed.

USE OF CROP RESIDUES

In developed countries crop residues are largely returned to the soil or, in some instances, may be used for maintenance of beef cattle during the winter (Anderson, 1978; Klopfenstein et al, 1987; Males, 1987). Where only the grain is used, the overall efficiency of utilisation of total energy from a crop such as maize is low. One hectare of maize may yield approximately 30 240 Mcal of metabolisable energy (ME) and 620 kg of protein in the grain and stalk (Table 1). When only the grain is used for human consumption or for livestock feed about 39% of the energy and 20% of the protein are utilised. When the bran and stover

Table 1. Production and utilisation of maize.

	Mcal ME[1]	Protein (kg)
Production ha^{-1}		
Grain	19 040	360
Plant	11 200	260
Total	30 240	620
Human or animal feed U.S.		
Grain	11 735	123
% total	38.8	20.0
Subsistence farms		
Grain		
Human consumption	11 735	123
Bran, animal feed	2 810	22
Stover, animal feed		
Milk	2 580	31
% total	56.7	28.4

1. Megacalories of metabolisable energy.

are also used as animal feed, total ME utilisation may be increased to over 56% and protein utilisation to 28% (Table 1).

Table 2 shows the high seasonal dependence of small farmers (1.3 ha) in southern India on crop residues (dry fodder). In this region milk sales are important, hence some purchased concentrates plus brans are used as supplements to maximise intake of the coarse feeds. Dry fodder provides 13% of feed dry matter from August to October, but 52% from January to April.

Table 2. Feed sources on mixed farms used for feeding buffaloes and cattle by season in southern India (kg $animal^{-1}$ day^{-1}).

	Jan-Apr	May-July	Aug-Oct	Nov-Dec
Green fodder[1]	2.22	2.20	9.06	6.19
Dry fodder[2]	5.87	4.02	1.15	4.55
Purchased concentrates	0.89	0.19	0.40	0.44
House concentrates[3]	1.51	0.65	0.40	0.16
Other[4]	0.08	0.34	2.31	3.27
Pasture ($h\ d^{-1}$)	3.31	3.40	3.23	3.46

1. Largely weeds removed from crops or regrowth of rice.
2. Maize or sorghum stover, wheat and rice straws.
3. Brans from preparation of human food.
4. Grasses harvested by women from footpaths, and neighbouring fields.
5. Communal grazing with realised intake of < 1 to 3 kg of dry matter per day.

African pastoralists are highly dependent on crop residues from their own small plantings or from crop farms to supplement grazing during the dry season. The deficiencies of grazing in northern Nigeria, a central district in Botswana and the Machakos District in Kenya are shown in Table 3. Estimates of intake from grazing by 250-300 kg cattle are expressed in relation to animal needs for body maintenance (1.0). In northern Nigeria, grazing normally provides sufficient energy from June to October for a cow to gain up to 1.0 kg per day (July to September) but grazing cannot meet the animal's energy needs from December through May, resulting in serious weight losses. Fluctuations in feed quality and quantity lead to low net weight gains of about 70 kg a year. In Botswana the feed is deficient for only about 4 months but grazing and browsing in Botswana requires greater energy expenditure than in Nigeria. Even so, animal gain could reach 90 kg per year. If sufficient grazing is available, there is less need for supplementary feeding in Kenya than in Botswana or Nigeria (Table 3). Expected animal gains would exceed 110 kg per year (Nsibandze, 1982).

Average rainfall in the three areas is approximately the same. Its distribution has a marked effect on the grass species and their nutritive value, which is highest in Kenya, somewhat lower in Botswana and least in Nigeria. In Kenya and Botswana browse adds significantly to feed quality and quantity. In Nigeria, heavy rains over a short period lead to rapid growth and maturity of grasses followed by marked decline in quality. As pointed out by Wilson (1982) and others, supplementary feeding is essential in much of the subhumid and semi-arid areas of West Africa. The need for manure on cropped areas and

Table 3. Estimates of monthly energy intake by 250-300 kg cattle on rangeland grazing in three areas in relation to maintenance needs[1].

Month	Northern Nigeria[2]	Central District Botswana[3]	Machakos District Kenya[4]
January	0.8	2.1	1.4
February	0.7	2.0	1.2
March	0.6	1.7	1.5
April	0.6	1.4	1.9
May	0.5	1.2	2.0
June	1.5	1.0	1.6
July	2.3	0.8	0.9
August	2.2	0.7	0.8
September	2.0	0.6	1.0
October	1.5	0.6	1.5
November	1.2	1.6	2.0
December	0.9	2.1	1.6
Mean	1.23	1.29	1.45
Average daily weight gain (kg)	0.20	0.24	0.30

Source: Adapted from McDowell (1985).

1. Example: January, northern Nigeria 250-300 kg cow has intake 80% of energy needs for body maintenance thereby losing weight but in July intake is 230% of maintenance needs when weight gain or milk yield can be high.
2. Rainfall 450-500 mm; 97% from late May to mid-September.
3. Rainfall 400-500 mm; 95% from late November to mid-May.
4. Rainfall 500-550 mm; long season March-June and short rains October-December.

the pastoralists' need for feed leads to strong interdependence between crop farms and pastoralists (Wilson, 1982).

An average pastoral unit requires about 10 breeding cows, a breeding male and associated stock for subsistence needs (Brumby, 1987). These animals may use about 100 ha of rangeland providing approximately 10 500 kg of total digestible nutrients (TDN) per annum, which is far below needs. In northern Mali average rangelands in normal years will provide about 50% of livestock needs, hence crop residues must be used to avoid large weight losses in the dry season.

Data have not as yet been collected to determine whether the interrelationships between crop farmers and pastoralists in West Africa have influenced the adoption of new varieties of grain crops due to possible changes in yield and quality of crop residues, but ILCA researchers reported low acceptance of high-yielding varieties of cowpeas in northern Mali because of low forage yield. Concerns have been expressed in northern Nigeria and other areas over the rapid expansion of maize production, because maize matures earlier than sorghum or millet, while grazing is still reasonably good. As a result, the quantity and feeding value of maize stover is markedly lowered by weathering before it is needed for feed.

FARMER DECISION-MAKING

1. Choice of crop

Subsistence farms attempt to sustain about 4.5 people per household, each needing about 200 kg of grain per year. The farm must thus produce a total of 900 to 1000 kg of grain a year. Farm size is 1.5 ha, with 1.0 ha planted to maize and beans, 0.3 ha to wheat and 0.2 ha to sorghum. Using local varieties and low inputs, maize yields 600 kg of grain, beans 150 kg, wheat 200 kg and sorghum 150 kg, giving a total yield of 1100 kg, about basic human food needs. There are two cows, one bullock, one calf, two sheep and three goats. Yield of wheat straw is about 200 kg (1:1 ratio with grain) (Anderson, 1978) and maize plus sorghum stover 3450 kg (1:5 or 6 ratio to grain yield, in local varieties). Thus, the total crop residue yield is about 3650 kg, which provides approximately 150 days of feed. This, supplemented with off-farm grazing, could maintain the livestock.

Cash flow is low so the farmers want to reduce the maize land to 0.5 ha and add 0.5 ha of cotton as a cash crop. A new variety of maize is used and fertilizer applied, giving a yield of 1000 kg of grain. Of this, 200 to 300 kg is sold to pay for purchased inputs. The ratio of maize stover to grain yield is reduced from 1:5 or 6 to 1:1.5 or 2, hence maize stover yield is reduced to 2000 kg. The cotton provides no feed except weeds, hence total crop residue for dry season feeding is reduced to around 2500 kg, resulting in only 100 days of feed. The cattle fare less well because the digestibility of the maize stover declined from 52-56% (sufficient energy available for maintenance needs plus some for production) to 42-45% digestibility (sub-maintenance needs in energy) (Sands, 1979). The farmer must choose between reducing stock numbers, which is unattractive due to loss of prestige and savings, purchasing feed for livestock, relying more on off-farm grazing or returning to the traditional system. Other farmers have followed a similar procedure thereby placing greater pressure on communal grazing. In the second year nearly 50% of the farmers withdraw from the maize-cotton programme, to the consternation of extension agents.

2. Change crop residue management

Crop residues are low in protein and phosphorus, marginal in calcium and high in fibre and lignin. As a result, digestion is slow, rate of passage is low and voluntary intake is limited, e.g. *ad libitum* intake of sorghum stover is 43% less than that of hay. Intake may be increased about 20% by chopping the residue (Anderson, 1978).

Maize or sorghum may be cut and stacked or shocked to reduce leaf loss from leaching or wind damage. Research has shown that stripping the lower leaves (below the ear on maize or the lower half of sorghum) increases feeding value. Topping maize after the grain has nearly matured also helps to preserve forage quality. Although these procedures improve feed quality, farmer acceptance has been low because of low visibility of return to the extra labour required. Assembling or storing crop residues may be a necessity where cropland is highly fragmented, such as often occurs in India; where the household is dependent on manure for fuel--India and Ethiopian highlands--; or where marauding animals have access to crop residues during the off-crop season. When these elements are not pressing, farmers prefer to graze the residues to reduce labour for storage or transport of manure to the fields.

Preservation of crop residues is, however, attractive where high-protein concentrates, such as cottonseed cake or grain brans, are available at modest prices. With supplement, intake of residues may increase 20 to 30% (Conner and Richardson, 1987; McDowell, 1985). Farmers generally accept supplementation as an initial move to increase milk output or to fatten cattle or sheep (World Bank, 1987).

3. Chemical treatment

Other papers at this workshop deal with this issue. In farmer decision-making, suffice it to say that, although research results show promise, acceptance on resource-poor farms is slow due to costs (labour and capital) and risks.

Chemical treatment could be more attractive if it were complemented with modifications in the farming system. Forage crops have not received much attention in cropping systems research (Gibbs and Carlson, 1986). From the example given in section 1 above, production systems and crops need to be developed that will best meet the dual-purpose needs of smallholders. Including forage legumes in the crop rotation can increase the yield of the subsequent crop and sustain soil fertility, and such rotations need investigation. Indirectly, forage legumes would increase returns from crop residues through higher intake and more efficient digestion. Availability of good quality forages for supplement may, however, lessen the attractiveness of chemical treatment.

4. Change the animal

In recent years a frequent recommendation is for smallholders to concentrate on goats and sheep instead of cattle or buffalo. The advantages of low investment, early maturity and better breeding efficiency are most often cited. This recommendation makes the assumption that all four species are equally adept in the utilisation of crop residues, but this is not the case (Demment and Van Soest, 1983; Hart and McDowell, 1985; McDowell, 1987a; 1987b; McDowell, 1986; McDowell and Woodward, 1982). Feeding strategy is an important feature in assessing suitability of animal species. The comparative digestive strategies of goats, sheep and cattle are given in Table 4. Figure 3 portrays how selective feeding behaviour influences whether a given animal species is widely dispersed or clustered in certain areas because of prevailing feed resources.

The two major types of *Bubalus bubalis* (swamp and riverine buffalo) are probably the best users of crop residues among domestic livestock. Buffalo are grazers with low selectivity (Figure 3); they have a wide muzzle, large gut capacity and a greater extent of fermentation in the rumen than cattle. The last two features result in slow passage of food through the digestive system. The buffalo is therefore an effective user of high fibre feeds. Their major habitat, the paddy rice area of Asia, verifies their ability to use rice straw. Their best niche appears to be as users of crop residues or to provide some returns from grazing marsh areas. Their efficiency on high-quality forage is lower than that of cattle.

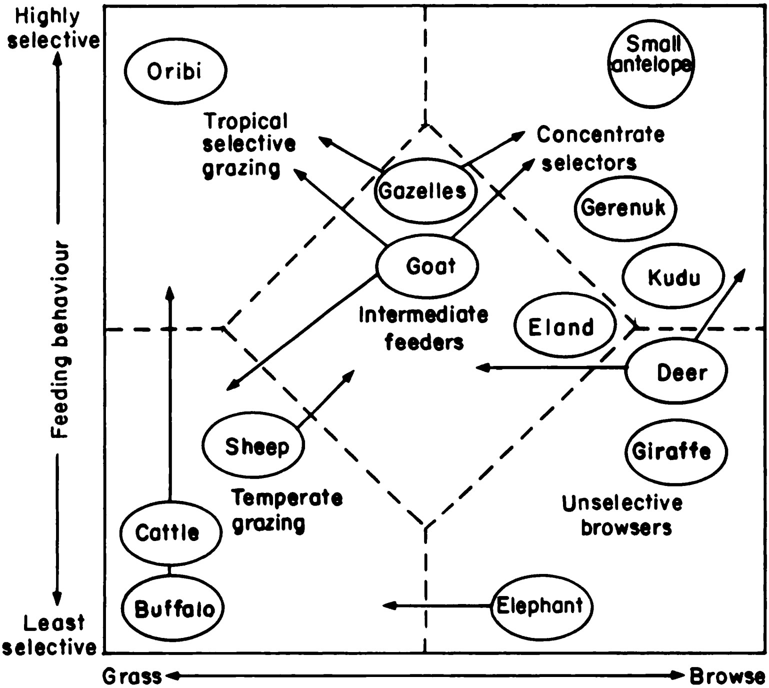
Cattle are classed as grazers with relatively low selectivity but are slightly more selective than buffalo. Their metabolic rate is lower than that of goats or sheep and their rumen retention time is longer, resulting in greater ability to digest fibre. The vast bacterial population in the rumen of cattle is a significant source of

Table 4. Comparative digestive strategies of goats, sheep and cattle.

Characteristics	Advantage	Limitation
	Goat	
Browser	Plant differentiation (morphological and seasonal)	Low utilisation of total biomass
Rapid passage	Higher intake possible, rapid passage of low-quality feed	More time required for eating
Low M_i [a]	Allows greater diet selection	High energy cost, increased maintenance requirements
	Sheep	
Grazer	Less travel energy needs, better use of total biomass	Diet limited to graze plants, plant differentiation not fully utilised
Intermediate rate of passage	Better fibre digestion	Forced to waste effort on low-quality feeds
Intermediate M_i	Permits higher cellulose fermentation	Decreased apparent digestibility
Small body size	Small absolute intake	High MR/GC[2]
	Cattle	
Grazer	High use of plant biomass	Diet limited to graze plants, plant differentiation limited
Slow passage	High fibre digestion	Forced to waste effort on low-quality feed
High M_i	High cellulose fermentation	Decreases apparent digestibility
Large body size	Low MR/GC, long legs, move rapidly	Mouth too large for plant differentiation

1. M_i value is that part of the faeces endogenously produced by the animal besides the undigested feed residue.
2. MR/GC = ratio of basal metabolic rate to gut capacity.
Source: McDowell and Woodward (1982).

Figure 3. *Free-roving animals will congregate in areas where feed is available and suits their needs. In tropical areas, animal size plays an important role in feeding behaviour. Small animals must be highly selective in choosing grasses and browse. This figure shows where familiar and exotic animals are found based on their feeding behaviour and preferred feed resources. Arrows indicate crossover may occur.*



Source: Adapted from Demment and Van Soest (1983).

protein. Thus cattle can survive on a diet of poorer quality grazing than can goats or sheep. Cattle can browse to a limited extent but their broad muzzle and slow bite rate does not make them effective browsers. Their absolute intake requirements are so great that there is generally insufficient high quality feed in tropical environments to sustain high levels of performance. There are morphological traits in the two species of cattle, *Bos indicus* (zebu or humped types) and *Bos taurus* (European or non-humped types) that can be significant in utilisation of crop residues. *Bos indicus* types have a longer, narrower head and smaller muzzle. They have nearly 25% less digestive capacity per unit of body size than *Bos taurus* types, which forces them to be slower and more selective feeders. On rangelands with shrubs for browse, *Bos indicus* will select a higher quality diet but will utilise less of the total forage dry matter. For example, zebu heifers grazing at the rate of 2.5 head per ha on improved grass pastures in Puerto Rico utilised 18.7% of the total DM while Holstein heifers of similar age and at the same stocking rate used 31.2% of the DM. A conclusion is that the feeding behaviour of zebu cattle is more responsible than other adaptation features for its high numbers in the tropics (Hart and McDowell, 1985). This feature is most important for grazing but is a limitation for zebu in use of crop residues. In India, Pakistan and other parts of southeast Asia, a buffalo cow fed *ad libitum* rice straw will maintain body weight and produce 1.0-1.8 litres of milk per day while local cattle will lose weight.

Goats are among the most selective of the intermediate feeders (Figure 3) and can use a wide range of plants. Their M_i (endogenous and microbial fraction of the faeces) values are lower than those of cattle and sheep (Table 4) because they generate less cellulytic bacteria in the rumen, which lessens cellulose digestion. The feeding strategy of goats is to select grasses when protein content and digestibility are high but to shift to browsing when leaves, bark and fruits have better nutritive value. Their small mouth and prehensile lips enable them to gather small leaves and flowers. Performance of goats may be low and mortality high on an exclusive diet of dry-season grasses in the subhumid zone but they will thrive in the same zone where there is a mix of browse, while cattle may be hard pressed to survive. Overall, goats are not good users of straws and stovers unless they are given an opportunity for high selection and receive some supplementary protein as bran or browse. Goats may die on an all maize stover diet or when penned on dry, mature tropical grass. Thus, goats have unique feeding strategies which can be employed to complement sheep or cattle for fullest use of certain ecosystems, but where crop residues are the main feed source goats are at a disadvantage.

Sheep tend to be mainly grazers but, as for goats, their body size requires they feed selectively. They are able to digest fibre effectively but on a diet mainly of crop residues, such as straw, they have the disadvantage of being forced to ruminate in order to clear their rumen; therefore, straw or stover gives low nutritional benefit for the energy expended. It is more difficult to relate feeding behaviour to area of concentration for sheep than buffalo, cattle or goats because they have high utility for meat and fibre as well as importance as a feature of the Moslem religion. They usually complement other species in maximising use of ecosystems.

McDowell and Hildebrand (1980) showed that even though the number of small ruminants per farm was low, most had cattle, goats, sheep and, in Asia, buffaloes. This indicates that: a) farmers are aware of the limitations of each animal species; b) they know the complementarity of species in utilisation of available resources; and c) they recognise that each species has a well defined function in the farm enterprise. It appears that for much of Africa cattle will tend to dominate as the best overall user of feed resources but in planning agronomic or livestock research strategies, small ruminants should be considered as part of almost all farm systems.

FUTURE

It is hoped that plant breeders will recognise a desire on the part of animal scientists to consider modifications in plant selection to maintain as high an animal utility as possible; that it will be agreed that further research on chemical treatment of crop residues may be warranted; and that the animal nutritionists will agree to move forward as rapidly as they can on standardisation of methodology for assessment of animal utility of crop residues and forages.

Hopefully the workshop will also explore the broader issues of production systems. We must appreciate that improvements in the feeding value of crop residues, whether by plant breeding, chemical treatment or both, will provide relatively low returns for smallholders, possibly 10-20%, in increased returns from animals. Predicted acceptance at this level of change will at best be modest because there are still problems of malnutrition among the animals. Improvements in straw quality could increase energy availability significantly but will do little to increase the availability of protein and phosphorous, which are in short supply in smallholder systems.

For ruminants such as cattle to express their full genetic potential for performance, the apparent digestibility (AD) value or the TDN content of the entire ration should exceed 70% on a dry weight basis. When AD is 60% performance will be intermediate and at 55% AD, production will be approximately 10 kg of milk per day or 0.5 kg weight gain per day. The minimum range in AD to assure body maintenance needs is 42-45%. At lower AD levels, animals lose weight. In the average feed supplies on mixed crop/livestock farms depending on crop residues for more than 100 days of feeding, around 10% of the total has AD 55% or more, 50% has an AD of 45-50% and 40% has an AD of less than 40%. Increasing the mid-range (50-55% AD) by 10 units will increase animal output by 20-40% provided total animal biomass remains constant.

If the workshop participants accept ILCA's long-range strategy on "thrusts" in research on milk and meat from cattle and small ruminants, animal traction and animal feed resources (ILCA, 1987), a needed focus in this exchange is much closer collaboration with the plant sciences including soils and agroforestry. Participants should be planning for research of ILCA and NARS on identification and development of varieties and commensurate production systems of leguminous and dual-purpose crops which can produce high-quality food and fodders.

ILCA's main thesis for shifts in strategy is the observation that:

> *In many cases livestock and livestock products are the most important source of the cash income of subsistence farmers. Small improvements in live-*

stock productivity quickly result in important income changes and in the availability of funds to improve the subsistence cropping patterns that characterise smallholder agriculture. (Brumby, 1987).

ILCA's strategy strongly suggests that research on production systems to meet the dual-purpose needs for smallholders will mean greater flexibility for all production systems, with or without livestock. Demonstration by ILCA researchers that rotation of forage legumes with food crops enhances yield of the subsequent crop and sustains soil fertility is most encouraging. Research on Vertisols in Ethiopia further shows ILCA's commitment to increasing total farm output.

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DISCUSSION

Ørskov: You suggested that zebu cattle are unlikely to survive on rice straw, yet in Bangladesh zebus are kept on this material.

McDowell: I doubt that they are kept exclusively on rice straw. Zebu cattle retain feed in the digestive tract for less time than do buffaloes. As a consequence their digestive capacity is 25% less. This means that they have to be more selective feeders and receive a more constant feed supply.

Little: There is generally no clear relationship between digestibility and intake for most feeds in the tropics, and therefore no direct relationship between increases in roughage digestibility and livestock performance. Nevertheless we generally consider that a digestibility of 50% leads to an intake of around 50 g kg^{-1} $W^{0.75}$ day^{-1}.

McDowell: I have no counter to your statements.

THE AVAILABILITY OF CROP RESIDUES IN DEVELOPING COUNTRIES IN RELATION TO LIVESTOCK POPULATIONS

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INTRODUCTION

The need to improve utilisation of crop residues in developing countries has received considerable attention in recent years, but there have been few studies on the availability of fibrous crop residues in relation to their potential for feeding livestock. The availability of crop residues is closely related to the farming system, the crop produced and the intensity of cultivation. The potential for use of crop residues as livestock feed is greatest in integrated crop/livestock farming systems. Where crop and livestock production are segregated, most crop residues are wasted. Crop residues are also wasted or used for non-feed purposes in many smallholder crop/livestock systems in developing countries.

In this study the amounts of crop residues (not including agro-industrial byproducts) available on farm have been estimated. Fibrous crop residues from cereals (straw, hulls, husks, cobs, awns, chaff etc) are the most important. Their use as livestock feed is limited mainly to ruminants. More detailed presentations of the methods used and global data are presented elsewhere (Kossila, 1984; Kossila, 1985).

METHODS

The following procedure is an outline of methods used to estimate the availability of crop residues in relation to livestock numbers:

1. Define the area of study (single farm, village, county, province, country, group of countries, region, world) and estimate the area of cropped land. Farm and village-level studies should be conducted before starting development projects aimed at introducing improved livestock production technology into smallholder farming systems in developing countries.

2. Select the crops to be included in the study, estimate the crop yield per area per annum and determine the yield of crop residues on the basis of grain yields. Examples of multipliers used for converting yield of cereal grain into yield of crop residue are given in Table 1. Multipliers for other important crops are given in Table 2. These are highly variable and should be determined regionally.

3. A livestock census should be taken if no reliable data are available. Livestock numbers should be converted into livestock units (LU). The researcher needs to decide which livestock unit to use: the tropical livestock unit is a 250 kg bovine at maintenance, whereas the LU used in most developed countries is a 500 kg bovine at maintenance. The choice should be clearly stated and not confused. Some examples of multipliers used to convert livestock numbers into LU are given in Table 3. However,

Table 1. Multipliers used to convert cereal grain yields to fibrous byproduct quantities in different regions.

	Africa	North & Central America	South America	Asia	Europe	Oceania	USSR
Wheat	2.0	1.5	1.2	1.3	1.0	1.3	1.0
Rice, paddy	---	---	---	1.3	---	---	---
Barley	1.5	1.2	1.3	1.3	1.2	1.3	1.3
Maize	3.0	2.0	3.0	3.0	2.0	3.0	3.0
Rye	---	---	---	2.0	---	---	---
Oats	1.5	1.3	1.3	1.3	1.3	1.3	1.3
Millet	5.0	4.0	4.0	4.0	4.0	4.0	4.0
Sorghum	5.0	4.0	4.0	4.0	4.0	4.0	4.0
Buckwheat	---	---	---	3.0	---	---	---
Mixed grains				3.0			

Table 2. Multipliers used in converting various commodities into dry-matter yields of their fibrous byproducts.

Commodity	Multiplier
Sugar-cane (fresh)	0.25
Roots and tubers (fresh	0.20
Pulses (dry)	4.00
Nuts (dry)	2.00
Oilseeds and oilplant residues (dry)	4.00
Vegetables, melons etc (fresh)	0.25
Fruits, berries (fresh)	0.40

comparisons of availability of fibrous crop residues per LU should be interpreted with care because of large differences among ruminants in feeding behaviour and nutritional physiology (Van Soest, 1982).

RESULTS

The quantities of fibrous crop residues (cereals, sugar-cane and other crops) in relation to livestock numbers by country are shown in Figure 1. In 1981, the average estimated amount of fibrous crop residues per LU was 2811 kg, with the highest regional average (5480 kg) in North and Central America and the lowest average (1019 kg) in Oceania. Quantity of fibrous crop residues increased from 1970 to 1981 by about 36% (Figures 2 and 3) whereas the number of grass eaters (i.e. ruminants) increased by only 10%.

Table 3. Multipliers used in converting livestock numbers into livestock units (1 LU=500 kg live weight).

	Africa	North & Central America	South America	Asia	Europe	Oceania	USSR
Horses and mules	0.9	1.0	1.0	0.8	1.0	1.0	0.9
Asses	0.6	0.7	0.7	0.6	0.7	0.7	0.7
Cattle	0.6	0.9	0.8	0.7	0.9	0.8	0.8
Buffaloes	------	------	------	1.0	------	------	------
Camels	------	------	------	1.1	------	------	------
Pigs	0.16	0.30	0.20	0.18	0.30	0.18	0.30
Sheep	0.08	0.11	0.10	0.09	0.11	0.11	0.09
Goats	0.07	0.08	0.07	0.08	0.10	0.10	0.08
Chickens & ducks	0.012	0.015	0.012	0.012	0.015	0.015	0.015
Turkeys	------	------	------	0.035	------	------	------

Figure 1. *Production of fibrous crop residues in different countries of the world in 1981 (tonnes DM per livestock unit of grass eaters per year).*

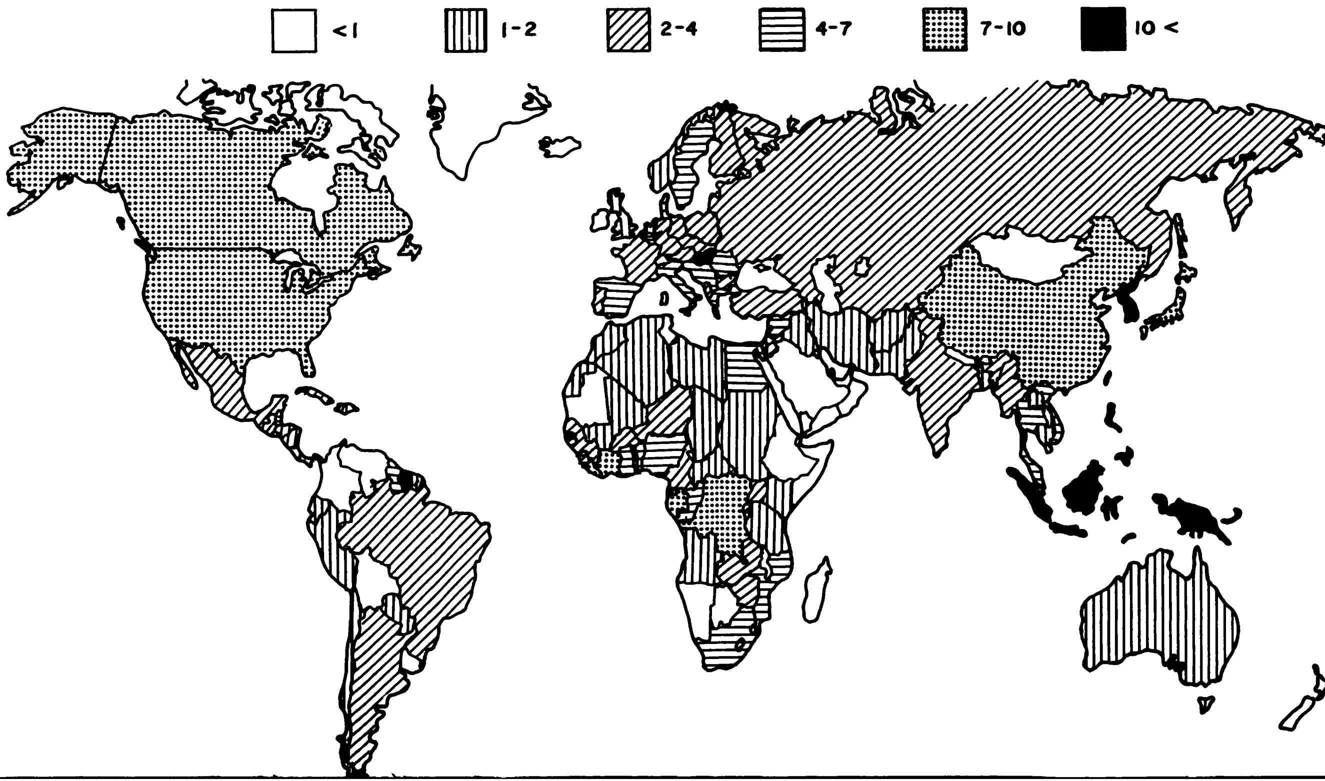


Figure 2. *World production of cereal crop residues, 1970–81.*

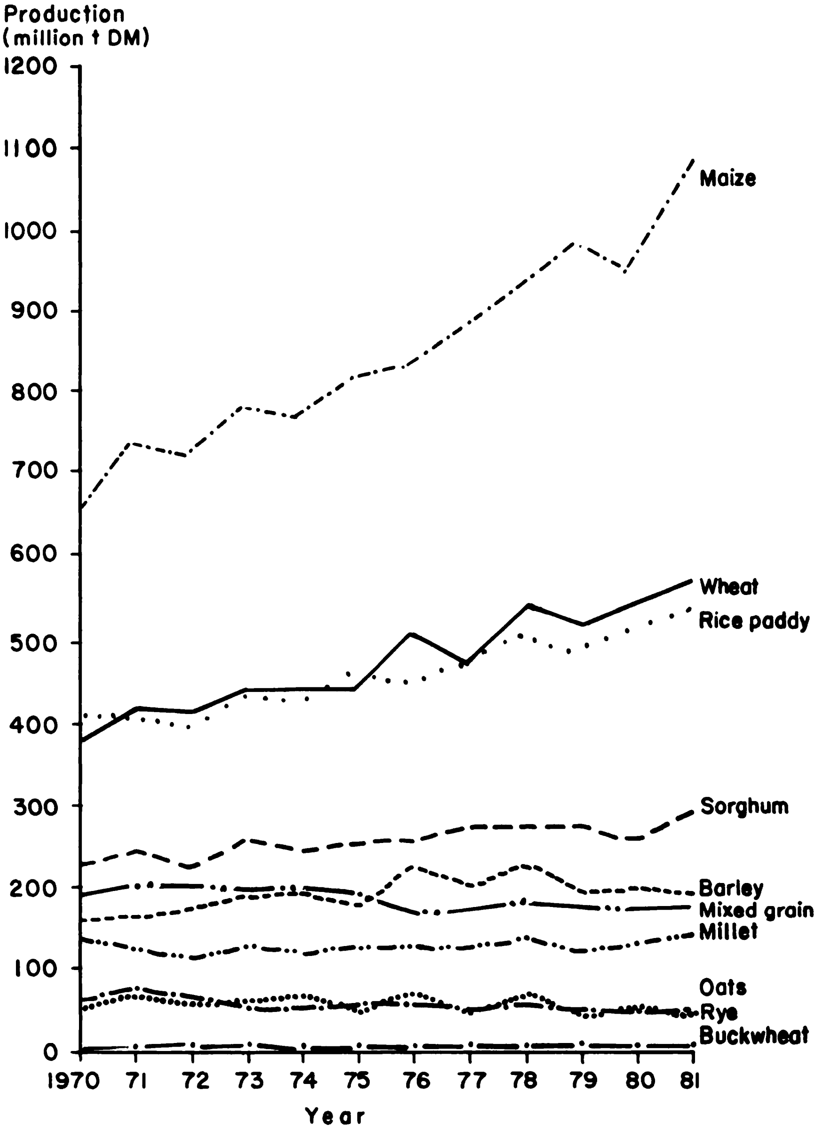
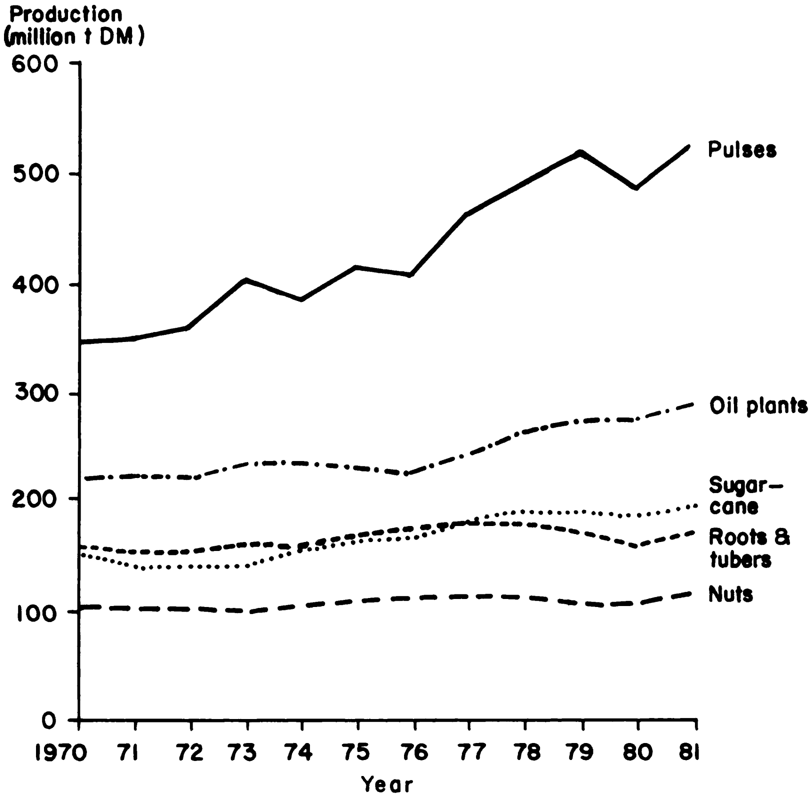


Figure 3. *World production of fibrous residues from pulses and other crops, 1970–81.*



In many countries the amount of crop residue exceeds the amount that can be used. These include the USA, Canada, most European countries, a few Near Eastern countries, a belt of countries from Mozambique to the southwest coast in Africa, China, Korean PDR, Korean Republic, and most countries and islands of Southeast Asia. Many other countries have a low ratio of available crop residues to grass-eater LUs. These include most countries in North, East and southern Africa and many countries in the Middle East.

In 1981, Africa had about 12% of the world population of grass eaters but produced only about 8% of the world's fibrous crop residues. The residues in greatest supply were maize (95.7 million tonnes), sorghum (55.2 million tonnes) and millet (51.4 million tonnes).

Most countries in sub-Saharan Africa with a low ratio of crop residues to LUs have large areas of arid to semi-arid rangelands, large livestock populations and relatively low production of cereals (Table 4). Countries with a high ratio were mainly in the humid zone of West Africa where cereal yields are higher but cattle populations are severely limited by trypanosomiasis (Table 4).

CONCLUSION

Large quantities of fibrous crop residues are already used as animal feed in many developing countries. There are also many areas in developing countries where ruminant livestock starve due to lack of feed. However, globally, it is apparent that cereal production has increased at a greater rate than livestock numbers over the last 10 to 15 years. These trends indicate that research should be strongly directed towards improving utilisation of fibrous crop residues as livestock feed.

Table 4. Quantity of fibrous crop residues per grass-eater LU, sub-Saharan Africa, 1981.

Quantity (kg DM LU^{-1})	Countries
<600	Botswana, Ethiopia, Madagascar, Mauritania, Namibia, Somalia
600-1999	Angola, Central African Republic, Chad, Guinea, Kenya, Lesotho, Mali, Sudan, Tanzania
2000-3999	Burkina Faso, Benin, Cameroon, Cape Verde, Comoros, Gambia, Guinea Bissau, Niger, Uganda, Senegal, Swaziland, Zambia, Zimbabwe
4000-6999	Burundi, Congo, Ghana, Malawi, Mozambique, Nigeria, Sierra Leone, Togo
7000-10 000	Gabon, Cote d'Ivoire, Liberia, Rwanda, Zaire

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DISCUSSION

Thomson: Cotton crop residues are important in Mediterranean countries such as Syria and Egypt. Could you comment on the availability and use of this material?

Kossila: Cotton residues were included in my calculations but much more information is needed on the amounts available for animal feeding compared relative to other uses.

THE IMPORTANCE OF CROP RESIDUES AS FEED RESOURCES IN WEST ASIA AND NORTH AFRICA

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INTRODUCTION

The importance to farmers of crop residues for feeding ruminant livestock has long been neglected, if not falsely maligned, by scientists who define their success only in terms of grain yield per hectare. The error in this neglect is proven when a farmer rejects an "improved" cultivar because of its clearly inferior straw quality.

This paper argues that we are really dealing with joint products of cropping in North Africa and West Asia, rather than simply incidental residues. Ruminant livestock add value to and stabilise many farming systems by providing means for storing wealth and for marketing large parts of the farm's crop residues.

High-quality crop residues are in short supply in this region. Well-directed plant breeding, in collaboration with animal nutritionists, may be the surest and most economical path to enhance these important feed resources: new cultivars which, from the farmers' viewpoint, are truly "improved".

JOINT PRODUCTS OF CROPPING

The farming systems approach to research requires us to look at problems and evaluate possible solutions from the viewpoints of farmers. In much of North Africa and West Asia, when farmers sow their crops they expect to get feed for their livestock at harvest (and sometimes before), and this expectation is clearly part of the reason for growing the crop and managing it in the ways they do.

In economic terms, the livestock feed and the grain are considered by many farmers as "joint products." In some cases, from the farmers' viewpoint, the market value of the harvested straw from a field equals the value of the grain: e.g. lentil straw in Syria (Nordblom and Halimeh, 1982), and wheat straw in Egypt (Sallam et al, 1986). These are, of course, not representative of all straws in all countries: the point is that grain is neither the only, nor always the main, reason for growing a crop in this region.

One would like to have a simple term that captures the sense of "all those joint-products of cropping which go for livestock feed and which are not grain." Finding no such word, I will stick to "crop residues for livestock." This recognises that other greater or lesser proportions of the non-grain biomass are shattered, trampled, ploughed under or burned in the field, hauled away for use as fuel, in manufacturing (e.g. for paper or press board) or for animal bedding.

There is even competition between use of crop residues for livestock versus their use to maintain soil organic matter balances and stabilise crop productivity, particularly where soil erosion is a threat (Anderson, 1978). This has been flagged as a serious problem in the drier farming areas of Syria where the livestock have been winning the competition and the soils losing (Jaubert and Oglah, 1985). Organic-matter levels in these soils, after many years of almost complete removal of crop biomass, are very low (Cooper et al, 1987). Research is now underway at ICARDA to determine the effects of various stubble management and tillage practices on soil structure and stability. Water infiltration rates and water-holding capacities are aspects of special interest. Control of erosion and sustained levels of productivity are the goals. Even though standing stubbles can be sold for grazing, the loss of some of these fees may be more than compensated by long-term sustainability of crop production if stubbles can be managed to the soil's best advantage.

The somewhat derogatory terms, "crop residue" and "agricultural waste" must have originated in the temperate climates of northern Europe and the British Isles. In a review of alternative practical methods for exploiting cereal straws, as fuel, feed and fertilizer, Staniforth (1982, p. 1) stated that:

> *the use and disposal of a huge and growing surplus of straw presents British agriculture with one of its most serious problems.*

It is easy to understand this European perspective on crop residues as an over-abundant obstacle to clean tillage and clean air. Crop residues are often difficult to deal with: scattered over the fields after harvest, they are invariably bulky, awkward and costly (per unit of weight or value) to collect, transport and store.

In a global review of potential uses of crop residues as animal feeds, Kossila (1985) pointed out that countries with the highest ratios of "grain eating" to "grass eating" livestock also tend to have the highest productions of fibrous crop residues relative to numbers of "grass eaters." In Europe, "grain eaters" (in 1981) amounted to nearly 34% of total livestock units; in contrast, for the majority of Middle Eastern countries, "grain eaters" comprised less than 5% of total animal units (Kossila, 1985, pp. 5 and 8)

In drier and warmer rainfed farming areas of North Africa and West Asia, farmers' perspectives on crop residues are often fundamentally different from those in Europe. Here, crop residues are seen by farmers as highly desirable joint products of cropping. Cropping intensities (and crop yields) in these rainfed systems are low, with gaps of several months between harvest of one crop and sowing of the next. This often coincides with the rainless summer months, affording considerable flexibility in handling crop residues in the field and allowing time for this to be done by labour-intensive methods, using labour of low opportunity cost (i.e. of women and children).

As in Europe, however, crop residues in this region are bulky and expensive or impossible to transport (e.g. stubbles). These materials are always cheapest in the places where they are produced. The demand for their use as livestock feeds is derived from the demand for animal products and the other reasons farmers maintain livestock. The existence of abundant crop residues can create an economic niche for ruminant livestock in the area.

Several cases of "joint products," which are not strictly "after harvest residues," should be mentioned because they are part of the bio-economic context. When Pakistani farmers sow wheat, they expect to take two or more hand-cuttings of the vegetative growth for livestock feed before allowing the grain crop to mature (ICARDA, 1987, p. 18). In northeast Syria, barley crops in the green stage are grazed by sheep in winter, then allowed to mature to produce grain and straw (Nordblom, 1983a). In Egypt maize leaves are stripped from plants before harvest (Soliman et al, 1985). There is also the flexibility to use grazing ruminants to harvest a poor crop in a year when rains fail, where the expected value of the harvested crop, minus the harvesting cost, is less than the value of the crop for direct grazing (Nordblom, 1983b; Mazid and Hallajian, 1983). This practice is widespread in northern Syria (Somel et al, 1984) and south-east Turkey (Yurdakul et al, 1987), with the proportions of farmers doing this varying from district to district and from year to year, depending on crop and pasture growth and on cost/price conditions.

Often there are distinct tradeoffs between the options--green forage, grain and crop residues following harvest--in terms of quantity, quality and time of availability (Miller et al, 1979, p. 40).

SHOCK ABSORBERS FOR FARMING SYSTEMS

Ruminant livestock provide the only means to capture economic value from many pasture resources and crop residues. They are flexible in dietary inputs and levels of output performance, in terms of fertility and rates of milk and meat production. They are mobile and may be trekked to the various grazing sources where and when they are cheapest: around the farm, to the roadsides, to native pastures etc. Their flexibility includes the important capacity to gain weight when feed is good and cheap, then metabolise the stored fat to survive periods when feed conditions are poor.

The ability of ruminants to utilise many combinations of pasture, crop residues and concentrate feeds, and to accept changes in these through the seasons of the year and between years, is a great advantage. This allows farmers to use the cheapest available feeds consistent with desired performance. At many sites, these combinations alter from year to year as conditions change (Mazid and Hallajian, 1983; Nordblom, 1983a and 1983b; Mazid et al, 1984).

The key role of crop residues is in the maintenance diets of breeding stock: diets for lactation or work require higher energy concentration, as do fattening diets. In Syria, for example, crop residues form the main diet of breeding sheep flocks, with concentrate feeds (mainly barley grain) added at lambing and during lactation (Jaubert and Oglah, 1985; Nordblom and Thomson, 1987; Nordblom, 1987; Thomson, 1987).

When prices for slaughter animals or dairy products are high relative to grain prices, farmers are tempted to increase livestock production by adding grain to the diet. For the farmer, grain in fattening and dairy diets can be highly economical (Brokken et al, 1980; Heady and Bhide, 1984) and, because of the demand for grain by dairy and fattening enterprises, surplus grain production and storage capacity is encouraged, often well beyond that needed for direct human consumption.

When grain for human consumption is in short supply, reflected in high prices relative to dairy products and meat, livestock diets may be shifted towards lower energy maintenance levels and away from grains. In emergencies, central governments may intervene to accelerate this shift. Livestock may also be sold for slaughter or for transport to areas with cheaper feed. Thus, the grain that would have gone to produce high value meat or dairy products can be diverted quickly to direct human consumption, serving a crucial role for human survival in emergencies (Sarma, 1986, p. 50). The crop residues which are jointly produced with the extra crop areas add to the ease with which grain can be diverted rapidly from livestock to human consumption.

Among the world's developing regions, North Africa and the Middle East have the highest projected growth rate (6.1% annually) in the use of major food crops as livestock feed. Human consumption of base staples is expected to grow by only 2.5% annually to the turn of the century, just less than the projected rate of population growth: livestock and poultry are expected to take larger shares of per caput use of base staples as higher incomes are achieved (Paulino, 1986, p.40). According to Sarma and Yeung (1985, p. 57) demand for feed and fodder will increase rapidly in the coming decades, encouraging more intensive land use and more efficient use of crop residues.

Finally, livestock often serve as the store of farmers' wealth: liquid, mobile, prestigious and more secure than other forms of savings in many parts of the region. The combined flexibilities of ruminant livestock, recognised since antiquity, means they serve as reliable "shock absorbers," to provide important physical and economic cushioning, thereby stabilising and enriching the quality of life in many farming systems. It is in the context of such integrated use of ruminants in farming systems that we consider the importance of crop residues in North Africa and West Asia.

CROP RESIDUES FOR LIVESTOCK

A basic problem in the study of national or regional feed trends is the lack of reliable data on feed use (Sarma, 1986, p. 51). This is particularly true of most crop residues and of grains which are fed on the farms where they are grown and never enter the market. Because they are mobile and a key store of wealth for farmers in this region, livestock are notoriously difficult to count with confidence. These facts mean one must make a number of assumptions about the national aggregations of livestock numbers, and national aggregations of diverse classes of crop residues, in order to present a simple picture of the use of these feed resources. This section of the paper is devoted to those assumptions.

A simple picture is necessarily abstract and incomplete: in this case, the list of omissions may be longer than that of inclusions. To begin with, only 15 countries of the region have been selected for discussion: Afghanistan, Algeria, Egypt, Ethiopia, Iran, Iraq, Jordan, Libya, Morocco, Pakistan, Saudi Arabia, Sudan, Syria, Tunisia and Turkey; these were arbitrarily chosen by the author only to illustrate some of the general tendencies.

Only sheep, goats and cattle have been selected for review in this paper. Inevitably this has resulted in missing some important classes of livestock (e.g. buffaloes in Egypt and Pakistan, camels in Sudan etc), but these three classes are found in large numbers in all 15 countries and offer grounds for rough comparisons. Data on livestock numbers, by country for 1965 and 1985, were taken from the *FAO Production Yearbook*. An arbitrary weighting scheme was used to aggregate "animal units" in each country: one "animal unit" equals one cow or five sheep or five goats. The result (Appendix 1) is a very gross indicator of comparable "animal units" for each country in 1965 and 1985.

The crops producing "residues for livestock" are likewise numerous. Ten crops were chosen for discussion purposes--wheat, barley, rice, maize, sorghum and millet (as one), sugar-cane, sugar beets, lentils, faba beans and cotton--since these are the main sources in this region. What is wanted here is a gross indication of dry matter quantities of the various residues offered to livestock, not simply the total quantities produced.

Beginning with the national crop statistics published in the *FAO Production Yearbook* series, a number of assumptions are needed in order to estimate the amounts of crop residues for livestock grazing and feeding. The assumed multiplication factors (applied in Appendix 2), for the 10 classes of crop residues are explained below:

WHEAT: Beginning with a harvest index of 47 (grain is 47% of the above-ground biomass), and considering burning, trampling, shattering and handling losses, it is assumed that only 0.8 kg of wheat straw and chaff is offered to livestock for each kilogram of wheat grain harvested.

BARLEY: With a harvest index of 41, it is assumed that 1.2 kg of residue is offered to livestock for each kilogram of barley grain harvested. This allows for some field losses but considers that barley straw is more fully used than wheat straw, partly because barley is grown in drier areas where feed is in shorter supply relative to livestock numbers.

RICE: Rice has a similar harvest index to barley, but lower feed value than barley straw (much rice straw is used for bedding, fuel and paper manufacture). It is assumed that only 0.6 kg of rice straw and chaff is fed for each kilogram of rice grain harvested.

MAIZE: Leaf stripping for fodder and use of the best parts of harvest residues by livestock amount, it is assumed, to only 2 kg of dry matter for each kilogram of maize grain harvested. The tough lower stalks are used for fuel.

SORGHUM AND MILLET: The ratios of grain to total above-ground biomass are taken to be about 1 to 6 for both crops. Given that the poorer part of the stover is used for fuel, the dry-weight ratio of residues fed to grain harvested is assumed to be only 3 to 1.

SUGAR-CANE: It is assumed that only one kilogram of sugar-cane residue dry matter (stripped leaves and bagasse) is offered to livestock for every 10 kg of raw cane harvested. This considers that about 60% of the bagasse is used for fuel in the sugar mills (Ensminger and Olentine, 1978).

SUGAR-BEET: The tops are normally grazed by livestock after the beets are harvested, amounting to about 30 g dry-weight for every kilogram of raw beets. About 1 kg DM of beet pulp goes to livestock feeding for every 15 kg of raw sugar-beet harvested. Therefore, total dry-weight residues for livestock feed (tops and pulps) are assumed to amount to only 0.1 kg for each kilogram of raw beet harvested.

LENTIL: Lentil crops are characterised by harvest indices which increase with increasing seed yield; and in this region great care is taken in hand harvest of the crop to preserve the residues for livestock feed (Nordblom and Halimeh, 1982). For the sake of simplicity, however, it is assumed that 1 kg of lentil crop residue is available to livestock for each kilogram of seed harvested.

FABA BEANS: The residues of this crop are used for feed and fuel in this region (Salkini et al, 1982). Allowing that the tougher stem parts go for fuel, it is assumed the amount of faba bean leaf and stem dry matter used as feed equals the weight of seed harvested for human consumption.

COTTON: In this region, cotton seed and the leaves of cotton plants are important livestock feeds, and the woody stalks are used for fuel. It is assumed that the dry weight of leaves grazed, plus the amount of seed material fed to livestock, amount to 2 kg for each kilogram of cotton seed harvested.

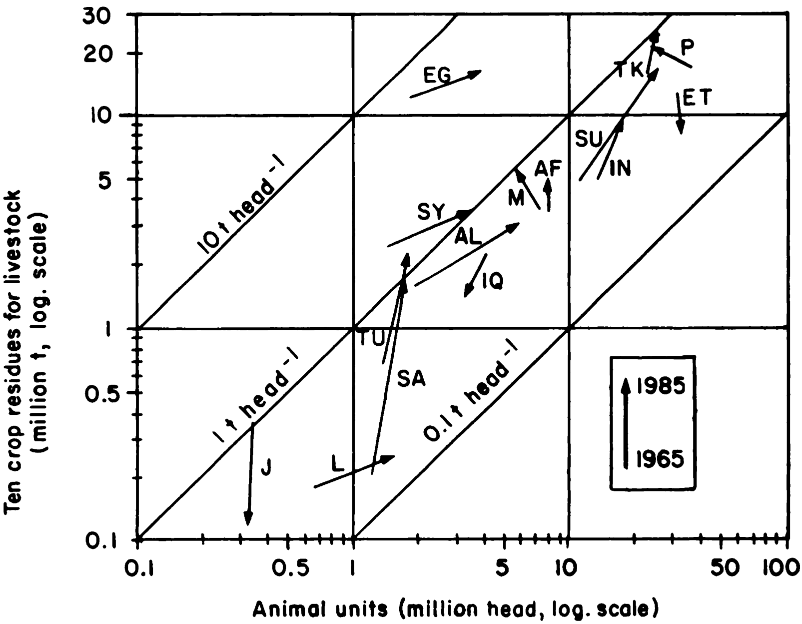
Using these weighting factors, estimated amounts of "crop residues for livestock" were derived from the FAO data for each crop, for both 1965 and 1985; these are given in Appendix 2 as a service to those who do not agree with my weighting scheme. As is also the case in Appendix 1, readers can find the original FAO estimates and make their own "corrected" aggregations.

AGGREGATE LIVESTOCK AND RESIDUES

The results of these gross aggregations of "animal units" (in millions of head) and of "10 crop residues for livestock" (in millions of tonnes) are given in Figure 1 and Table 1. Use of the arbitrary multipliers in deriving these results reduces any discussion of significant digits to a simple warning: anything beyond the first digit cannot be trusted. This is not a great worry for the present purpose since we find differences, in some cases, of two orders of magnitude between countries, and large shifts over time within countries: it was most convenient to plot these values on log scales.

One satisfying point in presenting such estimates is that all readers will be pleased in some way: those who are well informed on the crop-livestock relations in any of these countries will be pleased to attack my figures on solid grounds (1) of omitted classes of livestock and crop residues, (2) of the arbitrary weighting used in the aggregations, and (3) the inherent limitations of the data sources; these people and others may be pleased with the similarities found, across large and small agricultural sectors, in the indicated relations between livestock and crop residues for livestock.

Figure 1. *Sheep, goat and cattle "animal units" and crop residues for livestock in selected countries of North Africa and West Asia, 1965 and 1985.*



The diagonals crossing Figure 1 are lines of constant quantities of residues offered per animal unit, and succeeding diagonals differ by one order of magnitude: the upper of these represents 10 tonnes (t) of residue per animal unit, the middle diagonal is one tonne and the lower line is 0.1 t per animal unit. Although there were great differences between countries in absolute quantities of residues for livestock and in livestock numbers, the relative quantities (t head^{-1}) were remarkably similar in 1965 and 1985. The 15-country average was about 0.9 t head^{-1} in both 1965 and 1985, with the majority of countries showing increases in both crop production and animal inventories. Excepting Egypt, the 14-

Table 1. Sheep, goat and cattle "animal units" (AU) and crop residues for livestock (CR) in selected countries of North Africa and West Asia, 1965 and 1985.

	AU[1] (head x 10^6) (A)		CR[2] (t x 10^6) (R)		Residue per AU (t $head^{-1}$) (R/A)	
Country	1965	1985	1965	1985	1965	1985
Afghanistan	8.1	8.4	4.1	4.8	0.5	0.6
Algeria	2.1	6.0	1.6	2.9	0.8	0.5
Egypt	2.1	3.8	12.1	15.8	5.6	4.1
Ethiopia	34.0	34.2	12.2	9.0	0.4	0.3
Iran	14.4	18.0	5.0	8.7	0.4	0.5
Iraq	4.0	3.7	2.0	1.5	0.5	0.4
Jordan	0.4	0.3	0.4	0.1	1.1	0.4
Libya	0.7	1.5	0.2	0.2	0.3	0.2
Morocco	7.5	5.9	3.3	5.6	0.4	1.0
Pakistan	39.7	27.5	21.0	23.7	0.5	0.9
Saudi Arabia	1.2	1.8	0.2	1.7	0.2	0.9
Sudan	10.2	26.5	4.7	15.9	0.5	0.6
Syria	1.7	3.7	2.5	3.5	1.5	1.0
Tunisia	1.5	1.9	0.7	2.0	0.5	1.1
Turkey	24.0	28.0	14.3	28.7	0.6	1.0

1. See Appendix 1 for details on livestock aggregation.
2. See Appendix 2 for details on aggregation of 10 residues.

country averages were 0.6 and 0.7 t per head in 1965 and 1985, respectively, with standard deviations of about 0.3 t.

The existence of some 1.5 million donkeys, 2.2 million buffaloes and 0.1 million camels, in addition to the sheep, goats and cattle, effectively doubles the number of animal units given for Egypt in Table 1. This would reduce the apparent quantities of crop residue used per animal unit, bringing them closer to, but still well above, those of the other 14 countries. On the other hand, availability of native pasture grazing in Egypt is very limited in comparison with that in most countries of the region. The chief forage crop in Egypt, berseem clover (*Trifolium alexandrinum*), and crop residues form the main diets of ruminant livestock.

Assuming that a 500 kg animal unit (such as a cow) consumes 2% of its body weight in dry matter each day, yearly consumption would be 730% of body weight, or about 3.6 t. If one compares this with our estimated regional average residue intake of 0.9 t per animal unit, we must account for the remaining two thirds of the diet with forage crops, grazing of native pasture and concentrates. Some proportion of the latter is potential human food, bid away in the market by lactating and fattening animals because it is profitable.

Considerable attention has been focused on ways to improve the use (intake and digestibility) of residues for livestock by combining these materials in diets with supplements or by treating them with chemicals (ARNAB, 1986; Doyle et al, 1986; El Shazly et al, 1983; Kategile et al, 1981; Kiflewahid et al, 1983; Wanapat and Devendra, 1985). The practical difficulties, human and animal health hazards and economics of chemical treatment of straws (with sodium hydroxide, ammonia, urea etc), are matters of concern.

It is clear that chemical treatments are most effective where farmers have good control over the processes and adequate facilities. Such conditions are unlikely for the great majority of the region's small farmers in the foreseeable future. Therefore, chemical treatments will not be a widespread solution for increasing the value of crop residues in livestock diets for most small farmers.

A bright spot, offering the potential for widespread improvement in straw values, appears in the practical possibilities for breeding and selection of plant cultivars which produce both good grain yields and more digestible crop residues, enabling their greater substitution for grains and native pastures in ruminant diets. This will require collaborative efforts of animal scientists and plant breeders. The reward will be low-cost seed, profitably adopted by small farmers because it satisfies their needs for feed and grain. Priorities for this research should be the major grains: barley, wheat and maize, sorghum and millet, and rice. The time has passed when we, in our plant breeding work, could afford to ignore a main cropping objective of farmers in this region: to produce feed.

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Appendix 1. Sheep, goat and cattle numbers in selected countries of North Africa and West Asia, 1965 and 1985.

Country	Year	Sheep	Goats	Cattle	AU[1]
		----------	1000 hd	----------	
Afghanistan	1965	19 000	3 200	3 674	8 114
	1985	20 000	3 000	3 750	8 350
Algeria	1965	5 000	1 642	731	2 059
	1985	18 000	3 010	1 750	5 952
Egypt	1965	1 855	787	1 609	2 136
	1985	2 500	2 650	2 800	3 830
Ethiopia	1965	24 951	17 991	25 370	33 958
	1985	23 500	17 260	26 000	34 152
Iran	1965	24 500	17 600	5 945	14 365
	1985	34 500	13 600	8 350	17 970
Iraq	1965	11 040	1 845	1 455	4 032
	1985	8 500	2 350	1 500	3 670
Jordan	1965	803	651	65	356
	1985	990	500	35	333
Libya	1965	1 461	1 339	109	669
	1985	5 500	900	200	1 480
Morocco	1965	15 150	7 500	3 000	7 530
	1985	12 000	4 500	2 600	5 900
Pakistan	1965	10 800	11 600	35 200	39 680
	1985	25 037	29 726	16 549	27 502
Saudi Arabia	1965	3 300	2 341	102	1 230
	1985	3 800	2 454	540	1 791
Sudan	1965	8 660	6 850	7 100	10 202
	1985	19 000	13 500	20 000	26 500
Syria	1965	5 075	818	508	1 687
	1985	13 665	1 060	740	3 685
Tunisia	1965	3 767	527	592	1 451
	1985	5 220	940	620	1 852
Turkey	1965	32 654	21 162	13 211	23 974
	1985	40 391	13 100	17 300	27 998

Source: FAO Production Yearbooks 1967 and 1985.
1. AU = animal unit = 1 cow or 5 sheep or 5 goats.

Appendix 2. Estimated crop residues (1000 t) for livestock in selected countries of North Africa and West Asia, 1965 and 1985.

Country	Year	Wheat	Barley	Rice	Maize	Sorghum & millet	Sugar-cane
Afghanistan	1965	1 826	456	228	1 440	-	-
	1985	2 280	408	288	1 600	120	7
Algeria	1965	1 058	455	2	8	3	-
	1985	1 320	1 554	1	2	9	9
Egypt	1965	1 280	156	1 117	4 282	2 418	474
	1985	1 499	180	1 387	7 964	1 950	914
Ethiopia	1965	235	964	-	1 460	9 180	75
	1985	560	1 200	-	2 800	3 600	170
Iran	1965	2 400	1 200	507	28	54	25
	1985	4 800	1 980	660	100	135	215
Iraq	1965	804	968	119	8	18	-
	1985	520	840	63	64	9	9
Jordan	1965	222	114	-	-	30	-
	1985	80	36	-	-	-	-
Libya	1965	46	115	-	2	6	-
	1985	119	96	-	2	15	-
Morocco	1965	1 052	1 427	10	544	27	-
	1985	1 920	2 520	6	560	69	78
Pakistan	1965	3 700	156	10 677	1 086	1 110	2 500
	1985	9 280	193	2 700	2 060	1 560	3 214
Saudi	1965	118	38	2	-	45	-
Arabia	1985	1 360	14	-	8	285	-
Sudan	1965	45	-	1	24	4 041	19
	1985	63	-	4	80	14 487	480
Syria	1965	834	828	1	12	132	-
	1985	1 371	1 244	-	126	27	-
Tunisia	1965	416	216	-	-	15	-
	1985	1 120	823	-	-	18	-
Turkey	1965	6 904	3 960	130	1 890	180	-
	1985	13 626	7 800	159	3 800	45	-
Factors[1]		0.8	1.2	0.6	2.0	3.0	0.1

1. Data on crop yields from FAO Production Yearbooks 1967 and 1985 were multiplied by these factors to derive these estimates.

DISCUSSION

McDowell: The livestock units that can be maintained on a given quantity of roughage depends on the grazing behaviour of the animal species involved. You have given a factor of 8 to 10 sheep per livestock unit, but on the basis of grazing behaviour a factor of 5 would be more appropriate with a factor of 3 for goats.

Nordblom: This shows that small ruminants are less efficient. If the weight of 500 kg cow is converted to metabolic body weight it is equivalent to only five 50 kg sheep.

Fussell: We have observed in Niger that despite a 50% increase in the availability of crop residue, animal population increased by only 13%. It seems that the usefullness of crop residues as feed is low because the nutritive value of pasture is greater.

Nordblom: It cannot be said that animals are present because crop residues are available or, conversely, that crops are grown to provide residues for animals. Nevertheless the two are somehow associated.

SESSION 1

THE ROLE OF CROP RESIDUES AS FEED RESOURCES IN SMALLHOLDER CROP/LIVESTOCK FARMING SYSTEMS

General discussion

Capper: In recent years an enormous amount of research has been conducted on chemical treatment of crop residues but, as Drs McDowell and Nordblom have indicated, there has been disappointingly little uptake of the technology by farmers. Yet scientists continue to produce numerous publications on chemical treatment, neglecting the potential to exploit natural variation in nutritive value.

McDowell: The project I was involved with in India found that shortage of labour and storage space were major constraints. While researchers were present the project went well but when farmers were left to continue on their own initiative, the process broke down.

Van Soest: At Cornell we have analysed around 200 treated residues and have been impressed by the variability. Some materials actually decreased in value as a result of moulding or side reactions producing indigestible products. Urea treatment has very little effect on lignification. It causes swelling but intake is not increased.

Thomson: In North Africa and West Asia, ICARDA's mandate region, there is a deficit of crude protein in the feed resources. It would seem appropriate therefore to continue to look to urea as a source of protein supplementation.

Reed: There is a need for a clearer distinction between urea supplementation and treatment. In experiments conducted in the Ethiopian highlands urea treatment resulted in very little improvement in animal response.

Onim: The storage of crop residues and protection from weather and pests such as termites may be difficult for the farmer. On more intensive smallholdings in Kenya, for example, storage of crop residues may compete for space with threshing and living accommodation.

Ørskov: In many parts of Asia the situation is different, in that there are communal threshing grounds and crop residues are frequently stored nearby.

Nordblom: In ICARDA's mandate region the prices of grain from crops such as wheat and lentils are controlled by governments. This means that farmers often derive a large part of their income from the sale of crop residues. An example can be given from Egypt where farmers rejected a high grain yielding variety because of its inferior straw quality.

Capper: If government grain prices were adjusted to import/export parity prices what would have been the reaction of farmers to high grain yielding varieties with lowered straw quality?

Nordblom: I think their reaction would have been the same, i.e. they would have continued planting traditional varieties.

Ørskov: Artificially low feed concentrate prices in Egypt may distort the demand for crop residues and therefore their prices relative to grain.

McDowell: Farmer evaluation of the utility of crop residues is affected by the desire to maximise total income. The use of external resources such as feed concentrates together with residues produced on farm may result in a better overall utilisation of farm resources.

Ørskov: Animals have to live with fluctuating feed resources and a fluctuating output of products. The animal may provide the required flexibility by storing fat to be used for productive purposes at a later stage. Has Professor McDowell worked out how to use animal flexibility as an alternative to providing better-quality feed?

McDowell: Crop residues can only provide maintenance level nutrition. Thus any further deterioration in their nutritive value will reduce animal production. For instance, farmers in Mexico were growing traditional varieties with crop residue digestibilities of between 52 and 62%. CIMMYT varieties currently being released have crop residue digestibilities of less than 50%. A major factor causing this is a lower ratio of leaf to stem. The digestibility can only be restored to its former level by sodium hydroxide treatment, which is costly.

Nordblom: It may not be necessary for farmers to feed a balanced diet over all seasons. It may be to the farmers' advantage to allow their livestock to lose weight when feed is poor and in short supply and to exhibit compensatory growth when feed is plentiful.

Fussell: In West Africa, millet is grown in mixtures with legumes in a mixed cropping system. As a result the residues available are a mixture of stover and legume straw. The protein content of the latter improves overall feed value.

Pearce: I would like to caution against regarding urea as a cure for all problems of N deficiency. Considerable skill is required to optimise responses and it may be asking too much of a smallholder to achieve this. Supplementary energy and minerals are required in many circumstances to derive benefits from urea supplementation.

Witcombe: The multipliers used by Nordblom and Kossila for sorghum and millets to convert from grain yields to yields of crop residues differ and it appears that the latter are overestimates.

Nordblom: The figures I gave were for the amount of stover available.

Witcombe: I consider that the multipliers should be 4 for Africa and 3 for India.

SESSION 2

FACTORS LIMITING THE NUTRITIVE VALUE OF CROP RESIDUES

EFFECT OF ENVIRONMENT AND QUALITY OF FIBRE ON THE NUTRITIVE VALUE OF CROP RESIDUES

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INTRODUCTION

Straws and stovers are major feed resources for ruminants in Africa and other parts of the developing world and are more important than cultivated forages because of competition for land for human food production. These crop residues are high in fibre and the fibrous carbohydrates are their most important nutrients. Hence the nature and quality of fibre is of special interest. The environmental conditions under which the crops are grown and post-harvest storage conditions have a large effect on straw and stover quality.

Fibre is often used as a negative index of nutritive value in the prediction of total digestible nutrients (TDN) and net energy. Prediction equations assume that higher fibre means lower digestibility. The association between fibre and digestibility is strong in temperate forages because of the strong association between lignin and cellulose in first cuttings in temperate climates. However, this association is weak in tropical forages, straws and stovers and fibre cannot be used to predict digestibility of these feeds.

The role of fibre analysis in the evaluation of feed quality is complex: the total amount of fibre (plant cell wall) is a negative index, while the amount of available fibrous carbohydrates is a positive index. Coarse fibre is required for normal rumen function and metabolism and is a positive dietary factor. The physical characteristics of fibre (particularly particle size) are also important in regulating rate of passage, rumination, insalivation and the pH of the rumen (Van Soest, 1982).

The total fibre or cell-wall fraction of plants comprises cellulose, hemicellulose, lignin, cutin, silica and a variety of minor substances. The proportions of these components vary among parts of the same plant and also change as plants mature.

ANALYTICAL SYSTEMS

Forage dry matter can be divided by means of the detergent system into a readily available soluble fraction and a fibrous residue of limited availability (Van Soest, 1982). The nutritive value of the fibrous fraction is determined by the degree of lignification, while that of the soluble non-fibrous portion is completely available to digestion. Utilisation of starches and other non-fibrous carbohydrates is limited only by the extent to which they escape the digestive process by passing rapidly through the digestive tract (Van Soest, 1982).

The value of chemical analysis for evaluating forages has been called into question (Preston and Leng, 1987; Ørskov, 1987) on the basis that composition does not predict nutritive value, and that such analyses are too expensive relative to the amount of information provided. The critics would replace chemical analyses with nylon-bag degradability tests, and perhaps an analysis for nitrogen by Kjeldahl. They also charge that the originators of new chemical methods would convert all ruminant nutrition laboratories in the world to their procedures. This view ignores the purpose of detergent analyses which is to understand factors that limit the availability of energy and protein, and to correct the errors of proximate analysis and crude fibre by providing an accurate partitioning of cell-wall components into hemicellulose, cellulose and lignin (Van Soest, 1982).

Chemical analysis of feedstuffs is aimed at understanding why a given feedstuff exhibits its nutritional peculiarities. When this is understood, evaluation for causative and controlling factors can become routine, and not very expensive, since only the relevant factors are analysed. Unfortunately, the particular limiting nutritional factor varies among individual forages and feedstuffs, such that a single, universal analysis is not possible. Most of the misunderstanding of the use of chemical analyses for estimating nutritive value has arisen from incorrect application of methods. Proper application of analyses is directed toward solving specific problems, and thus the set of particular analyses will vary with the experimental situation.

The primary purpose of laboratory analysis is to characterise forages and feedstuffs so that nutritive value and performance in livestock can be related to chemical composition. This relationship has been the basis of compositional feeding tables for some time. Compositional data should include those components most pertinent to nutritive value. These vary among feeds but, for many feeds, determination of cell wall, lignification and nitrogen or crude-protein content will be sufficient. Ash, lipid and available carbohydrate contents are the next most useful factors to determine.

Proximate analyses including crude fibre and nitrogen-free extract (NFE) are inadequate for estimating nutritive value because they do not represent the components that limit biodegradability in the digestive tract. Nylon bag degradability is also unsatisfactory, because it measures digestibility and is not a chemical entity. Nylon bag measurements reflect rumen environment involving diet and animal differences and are thus inherently more variable than *in vitro* measurements of digestion. The latter are recommended for plant breeding studies.

Conceptual problems

The detergent system of analysis is intended to provide a biologically realistic description of forages and fibre. The use of fibre values for predicting digestibility is called into question by the chemical and nutritional non-uniformity of these fractions and thus the problem of crude fibre and NFE is not only one of erroneous analytical fractionation, but also of application in the form of empirical regression equations that attempt to estimate digestibility from fibre content.

The use of regressions of nutritive value on chemical composition assumes that nutritive value is determined by the chemical fraction measured. Applied to fibre, the assumption is that fibre limits nutritive value. However,the digestibility of fibre is limited by lignification and fibre is only secondarily related to digestibility through its association with lignin. Since lignification is greatly affected by environmental conditions, such as temperature, daylength, light and plant stress, the association of fibre with lignin content is highly variable. This is reflected in a positive association between fibre and lignin in forages growing in the spring (when temperature and daylength are positively related) and a negative association in the autumn. There is little or no association between fibre and lignin in forages growing in midsummer or under tropical conditions (Butterworth and Diaz, 1970; Van Soest, 1982). Despite this, acid-detergent fibre (ADF) or modified ADF (MADF) are used as principal criteria for estimating digestibility in both America and Europe.

The interactions of environment and climate with plant physiology and growth are sufficient to render associations between fibre components and nutritive value unreliable, and thus demolish the model that fibre regulates digestibility. The continued use of such regressions does not constitute a valid scientific operation, and is an abuse of the respective methods of analysis.

Chemical entities

Those who would justify empirical regression systems argue that ADF and NDF do not represent chemical entities and can therefore be treated like crude fibre. This overlooks the biological criteria for uniform chemical factors used in the establishment of detergent analyses, i.e. by the methods of Lucas (Van Soest, 1982). Crude fibre was intended as a determination of cellulose and, although imperfect by modern standards, is closely correlated with cellulose content.

Acid-detergent fibre is intended to represent lignocellulose and provide a preliminary step in the preparation of lignin, free from interference from protein. It contains small amounts of other cell wall components, viz bound protein and nitrogen, cutin, biogenic silica and micellular pentosans. However, these are of interest as unique fractions of very low digestibility. The determination of acid-detergent insoluble nitrogen (ADIN) for unavailable protein and the preparation of ADF for lignin and cellulose measurements are its main uses (Van Soest and Robertson, 1980).

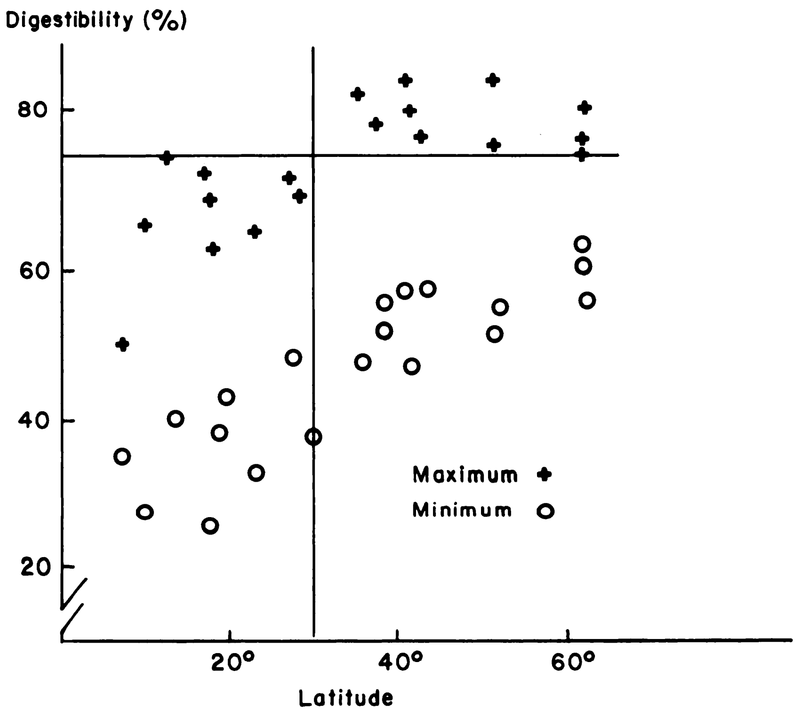
Neutral-detergent fibre (NDF) includes hemicellulose and represents the insoluble plant cell wall matrix that is cross-linked with lignin. The digestibility of the cell wall matrix depends on the extent of lignification. Pectin is not covalently bound to the cell wall matrix and is largely extracted by neutral detergent and is completely fermentable (Van Soest, 1982).

NDF contains the indigestible lignified matrix and associated components of the cell wall and represents the skeletal structure and volume of the plant. It is the only plant fraction that can account for rumen fill and voluntary intake of forage and that is highly correlated with both rumination and chewing time among a wide range of forages (Van Soest, 1982).

TROPICAL FORAGES, STRAWS AND STOVERS

The TDN of tropical forages averages 15 units lower than that of temperate forages (McDowell, 1972) due to effects of climate and management. However, reported maximum and minimum digestibilities from extreme immaturity to full maturity of forage grasses vary with latitude (Figure 1). The relationship between straw digestibility and latitude is probably similar to the minimum values in Figure 1.

Figure 1. *The relationship between digestibilities of perennial grass and latitude. Digestibility of first cuttings declines below 30° latitude. Vertical bar at 30° latitude is the approximate upper limit of the semi-tropics. Digestibilities of mature forages (o) decline progressively with decrease in latitude.*



Source: Van Soest (1982).

The tropics are the geographical regions that are free from frost and forages can grow continuously in this region if sufficient moisture is available. In temperate latitudes growth begins with the cessation of frost. Thus, maximum digestibilities are high and show no change with latitude above 30 degrees. However, in tropical areas growth begins at higher temperatures, usually after cutting or when rains end a dry spell. Survival of exposure to frost demands the accumulation of reserves to provide cold-tolerance, thereby increasing digestibility. The same effects are seen at high altitudes in the tropics and in arid areas (Van Soest et al, 1978).

The digestibility of plant material at maturity is determined by the cumulative environmental effects during growth and maturation. Level of digestibility is related to latitude, reflecting an inverse relationship with temperature.

Lower digestibility at higher temperatures is the result of the combination of two main effects: lignin synthesis and elevated metabolism. Higher temperatures increase lignification of the plant cell wall and promote more rapid metabolic activity, which decreases the pool of metabolites in the cell. Photosynthates are more rapidly converted to structural components, which reduces nitrate, protein and soluble carbohydrate contents and increases cell wall content (Deinum et al, 1968; Van Soest et al, 1978). Higher temperature increases the rate of enzymatic processes associated with lignin biosynthesis. Tropical plants are subjected to long nights during which soluble sugars and other highly digestible intermediates are respired, which lowers quality.

The general effects of environmental temperature upon plant growth and composition appear uniform in all plant species studied (Wilson, 1982). However, the quantitative effects of temperature upon forage quality vary with plant parts and with plant species. Temperature has its greatest overall effect on plant development in promoting the accumulation of lignified cell wall. This may be modified by growing conditions and species. For example, plant species that remain vegetative, whether by reason of too low environmental temperature during growth or by genetic character, are almost always less lignified that those plants that develop to the flower stage under similar environmental conditions (e.g. pangola grass). A physiological reason is that lack of flowering and seed development allows the required resources to remain in the leaves and stems promoting higher nutritive value. This effect is very important in cereals grown under conditions of poor grain production leading to a straw of higher nutritive value.

Another characteristic of tropical forages is the wide range in quality within the same standing plant (Van Soest, 1982). Animals tend to select better quality material and the difference in composition between what is eaten and what is refused may be considerable. In straws and stovers the nutritional quality of the leaf may be considerably higher than that of the stem. Thus a major factor affecting quality of straw and stover is the recovery of leaves. An exception to this is the case of rice straw where leaves are of lower quality than stems.

Straws and stovers are often chopped in order to reduce bulk, increase consumption and reduce wastage. This practice forces the animal to eat more of the low quality parts and reduces the nutritive value of that actually consumed. More selective feeding on the part of the animal is a recognised feeding strategy of goats and sheep which are more limited by their smaller metabolic size. These animals can be adversely affected by chopping forages. High producing dairy cattle are also sensitive to the physical form of forage.

Soil effects

Many cereals and grasses metabolise silica and deposit it in opaline form in the cell walls of leaves, reducing their digestibility (Jones and Handreck, 1967). Thus availability of soil silica can affect straw quality. This effect is particularly striking in rice which contains up to 20% silica, which is selectively distributed in leaves and seed hulls. Rice straws are low in lignin and silica is the prime factor limiting digestibility (Jackson, 1977; Van Soest, 1981).

C3 and C4 plants

The first stable products of photosynthesis in many tropical grasses are four carbon compounds, while those of dicots and most temperate grasses are three carbon compounds, hence the designation as C3 and C4 species. C4 plants are photosynthetically more efficient than C3 plants. Tropical C4 plants tend to accumulate large amounts of low-quality dry matter. These plants have fewer mesophyll cells between vascular bundles than C3 plants and, since mesophyll cells are comparatively unlignified and highly digestible, their proportion influences quality (Akin, 1980).

Not all C4 plants have lower nutritive value than C3 plants. Maize, for example, is a C4 plant developed from tropical ancestors. When grown in temperate regions its nutritive value is high. However, Deinum (1976) noted that maize grown under warm conditions reverts to many of its tropical ancestral characteristics and is of lower nutritive value (Table 1).

Table 1. Effect of environmental temperature on the *in vitro* digestibility of mature leaves at final harvest in maize.

Temperature[1] (°C)	17/12	20/15	25/20	30/25
OM digestibility (%)	88.6	87.2	80.8	79.5
Cell wall content (%)	53.3	53.0	56.8	53.4
Cell wall digestibility (%)	80.1	77.8	69.4	66.4

Source: Deinum (1976).
1. Day/night controlled temperature.

C3 and C4 plants coexist in the tropics but C4 forage plants (mainly grasses) dominate favourable environments because they are more aggressive and higher yielding. The C3 tropical forages include the legumes and grasses adapted to less favoured conditions. As a group they are higher in nutritive value, but yield less and are less responsive to fertilization. Agronomists in the tropics have favoured using the higher yielding C4 grasses, despite their lower quality.

Fibre quality

Fibre quality is defined as the ability to promote efficient rumen fermentation, and includes the potential digestibility and rate of fermentation of cellulosic carbohydrates, particle size and strength and cation exchange capacity. Graminaceous straws tend to be poor in these factors, although considerable variation exists. Legume fibre is superior in cation exchange capacity and rate of hydration to the average grass fibre, causing it to have shorter lag times after feeding and faster rates of fermentation. This occurs even in legumes of higher lignification. The shorter lag and faster fermentation are associated with higher consumption.

Grasses are characterised by high NDF and hemicellulose contents. As a result, intake of grass is lower than that of legume at a given digestibility. Grass fibre is also lower in lignin content than legume fibre. Thus, grass fibre is a better energy source for cellulolytic organisms than legume fibre, but its rate of fermentation and buffering capacity are lower. Lignin protects cellulosic carbohydrates from digestion but is responsible for much of the cation exchange capacity (McBurney et al, 1986). Thus lignin may have both a positive and a negative effect on fibre quality.

TREATED STRAWS

Treatment of low-quality forage to improve its nutritional value has usually employed alkali (Jackson, 1977; Sundstol et al, 1978). Removal of the limitation of lignification on digestion depends on either cleavage of the bond between lignin and carbohydrate or hydrolysis of the polysaccharide away from the lignified matrix. Most studies of the effects of roughage treatment have measured animal responses but not chemical changes in the forage, and thus most procedural evaluations used at the present are quite empirical.

Analysis of lignin is the most obvious means of determining the efficiency of delignification. However, the current practice of not washing the straw (for economic reasons) allows the cleaved lignin to remain in the product. Also NH_3-treatment with heat can elevate apparent lignin content through polymerisation of carbohydrates and proteins in the Maillard reaction. Unfortunately, lignin analyses do not distinguish cleaved from uncleaved or synthetic lignin and neither lignin nor fibre content reflects the improvement in *in vitro* digestibility of treated straws (Rexen and Vestergaard Thomsen, 1976; Ørskov, 1987). Subsequent studies indicate that the relationship between lignin and digestibility is considerably different in treated straws (Van Soest et al, 1984a). As a result, alkali-treated straws are often evaluated via rumen *in vitro* or cellulase digestion techniques.

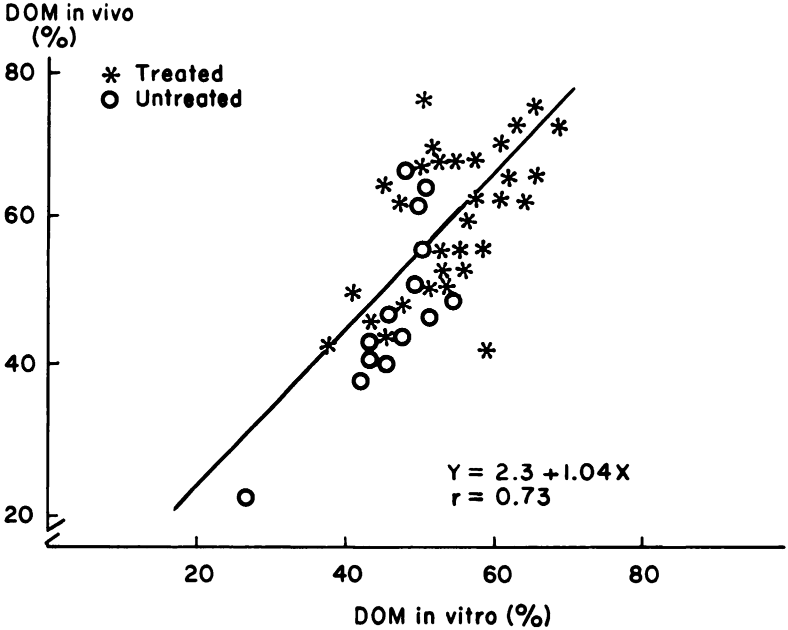
A chemical method to evaluate alkali-treated straw must distinguish cleaved lignin from uncleaved lignin. One procedure uses saponification of the isolated neutral-detergent fibre prepared without the use of sulphite (Lau and Van Soest, 1981). This measures the ester bonds left unhydrolysed after treatment with alkali.

The solution from neutral-detergent extraction can also be used to assess the quality of treated straws because cleaved lignin is soluble in neutral buffers and can be measured by UV absorption at 280 and 314 nm. Saponification with sodium hydroxide provides a solution which contains the residual lignin. Absorption at 280 nm results largely from phenolics, whereas ester linkages absorb at 315-340 nm; however, the latter wavelengths probably also include a component that is not ester related (Hartley, 1983). A third possible analysis is to determine residual lignin on an acid-detergent residue that has been prepared by sequential extraction with neutral detergent followed by acid detergent.

The cleavage of lignin-carbohydrate ester bonds in graminaceous straws results in the release of phenolic compounds into the soluble fraction (Hartley, 1983). The digestibility of the soluble fraction is depressed because the cleaved phenolics are not digestible (Neilson and Richards, 1978). This may partly explain the difference between rumen *in vitro* and *in vivo* digestibility coefficients in treated straws (Berger et al, 1979). This difference has not been explained by any laboratory measurements, although it has been attributed to faster passage of the treated forages due to changed physical structure (Berger et al, 1979).

McBurney (1985) examined 30 treated and 15 untreated samples of straws. Sixteen forages were treated with ammonia and 14 were treated with sodium hydroxide. Treatment tended to decrease NDF, but increased ADF, causing a drop in hemicellulose content. The effect was more pronounced with NaOH. The availability of additional nitrogen supplied by ammoniation varied widely: 0 to 66% of the additional nitrogen was in the acid-detergent indigestible nitrogen (ADIN) fraction which is unavailable to the animal and to the microbes. The relationship between *in vivo* and *in vitro* OM digestibilities is shown in Figure 2. *In vitro* measurements can both overestimate and underestimate *in vivo* values. The inverse

Figure 2. *The relationship between* in vivo *and* in vitro *digestibility of organic matter.*



Source: McBurney (1985).

correlation between lignin and digestibility was stronger in untreated than treated forages (Table 2). The correlation between digestibility and optical density of neutral-detergent extracts, which measures cleaved lignin-carbohydrate bonds, was positive in the treated samples. The solubles obtained after saponification of the treated forages contained intact lignin-carbohydrate bonds that were still susceptible to cleavage by alkali, and represent a measure of the inefficiency of treatment.

Table 2. Correlations between predictors of *in vivo* apparent organic matter (OM) digestion and *in vitro* apparent OM digestion.

	In vivo apparent OM digestion			*In vitro* apparent OM digestion		
Predictor	All	Treat.	Cont.	All	Treat.	Cont.
Number	46	30	16	46	30	16
Lignin %	0.33	0.42	0.51	0.53	0.63	0.70
NDS[1] OD_{280}	0.51	0.35	0.00	0.52	0.41	0.09
NDS OD_{314}	0.26	0.08	0.35	0.23	0.08	0.46
Sap. meq.[2]	0.62	0.36	0.37	0.60	0.35	0.29
SS[3] OD_{280}	0.64	0.68	0.21	0.66	0.64	0.34
SS OD_{314}	0.67	0.74	0.26	0.68	0.70	0.33

Source: McBurney (1985); Van Soest and McBurney (1985).

1. Optical density of neutral-detergent extract (OD units meq^{-1} OM).
2. Saponification value of neutral-detergent fibre (meq. base g^{-1} OM).
3. Optical density of solubles obtained from laboratory saponification of NDF (OD units mg^{-1} OM).

The improvement in digestibility due to treatment is highly variable. In some cases digestibility decreased, which appeared to result from moulding or other fermentation and an increase in net lignin and phenolic absorbance from the formation of Maillard products from heating. However, much of the variation in efficiency of treatment may be due to buffering capacity, which differed widely among the straws (Table 3). No current recommendation for straw

Table 3. Buffering capacity means ($\bar{X}$) and standard errors (SE) of a subset of control feeds.

Feed	n	$\bar{X}$	SE	Coefficient of variation (%)
Cereal straw	24	4.8	2.8	58
Grass	7	14.5	5.7	39
Bagasse	2	7.1	5.8	82

Source: McBurney (1985).

treatment considers buffering capacity. Buffering capacity is related to cation exchange capacity, one of the criteria of fibre quality. Ironically, much of the exchange capacity is lost upon alkali treatment of fibre.

Generally, alkali treatments lack quality control and are expensive relative to the increase in nutritive value obtained. This severely limits their application, and it may be more realistic to supplement nutrient-deficient straws than to treat them.

Buffering capacity and cation exchange

Exchangeable groups in the plant cell wall include carboxyl, amino, nonhydrogen-bonded hydroxyls, and phenolic hydroxyls, all of which may bind metal ions (McBurney et al, 1986). Thus the surface properties of fibre, i.e. hydration and cation exchange, are correlated (r about 0.7) and influence cell wall fermentation. The lag between ingestion and fermentation is related to how fast the fibre becomes hydrated and subsequent attachment of microbes. The amount of fibre digested after 6-12 hours of incubation is highly related to feed intake. Microbes have negatively-charged cell walls (Stotzky, 1980) and recognise and attach to fibrous particles by their exchangeable surface. This attachment requires formation of ligands between the microbial cell wall and fibre by divalent cations (probably magnesium). The cation exchange capacity of the fibre is its ability to bind and hold metal ions on its surface in much the same way that clay minerals hold cations in soil. The exchange serves as a bank exchanging K, Ca, Na, Mg for hydrogen when the pH drops and recharging as cations become available when saliva and ingesta are mixed. An advantage of this regenerable bank is that ruminated fibre passing down the digestive tract contributes buffering action further down the gut.

The buffering capacity of feedstuffs derives in part from the physical effects they elicit in the rumen and during rumination and ensalivation. Eating and rumination promote salivary flow containing much buffer that neutralises acids produced in fermentation. Fermentation of carbohydrates results in production of large amounts of organic acids, which must be removed by absorption to maintain pH and the normal rumen environment. Recycling of mineral ions is also important in maintaining rumen pH. The more slowly digested solid matter--fibre--contributes most to the maintenance of normal rumen environment. Tropical grasses and straws have low exchange and buffering capacities, and supplementation with starchy concentrates renders the rumen sensitive to acidotic conditions, which reduce rumen efficiency and net feed intake. Tropical legumes and citrus are high in exchange and buffering capacity and are useful supplements.

Microbial ecology

Quality forage fibre is also associated with microbial efficiency. Fibre-digesting bacteria manufacture more cellular protein than do starch-digesting bacteria because of their lower maintenance costs, the relatively high ATP yield of acetate fermentation and evolutionary selection for cellular storage. Rumen organisms have substrate preferences and can be divided into competitive consortia of mutually symbiotic species. For the purposes of this discussion they can be conveniently divided into: (1) fibre digesters and (2) those that specialise in starch (such as *Streptococcus bovis*) and more soluble carbohydrates. The second group tends to be adventitious, producing lactic acid at the expense of cellular efficiency. Rapid production of lactic acid reduces pH and thus renders the environment more favourable for their growth because low pH is more inhibitory to the slower digesting organisms dependent on cellulose and hemicellulose. The rate of carbohydrate digestion is set by the physicochemical limitations of the substrate, which in turn limit bacterial efficiency. The combination of slow fermentation rate and competitive passage leads to inefficient use of the potentially digestible carbohydrates, with low microbial output and increased faecal losses.

There are important relationships between fermentation rates of carbohydrates and microbial efficiencies, i.e. production of microbial protein per unit of feed digested in the rumen. The fermentation rate sets the amount of feed energy available to rumen bacteria per unit time. Faster digestion provides more food, which dilutes the energy costs of maintenance and leaves more energy for growth and production (Sniffen et al, 1983).

Bacteria have a maintenance requirement that must be met before growth can occur. The maintenance requirement of cellulolytic bacteria is one sixth that of bacteria that ferment soluble starch and sugar (Sniffen et al, 1983). The type and quality of carbohydrate can have considerable impact on rumen microbial yield because carbohydrates are degraded at different rates. Cellulolytic bacteria grow slowly and a decrease in fibre quality can dramatically reduce yield by reducing their rate of digestion and growth. This limits the utilisation of straw, stovers and tropical grasses, which tend to be slowly digested.

CONCLUSIONS

Straws and stovers contain large amounts of carbohydrates, mainly in the fibre, but availability may be low. Long lag times and slow fermentation are probably the main factors that limit intake and utilisation of straws and stovers. Tropical forages, straws and stovers are of lower quality than those from temperate regions because of environmental effects (temperature and daylength) on plant growth. Relationships between chemical composition and measures of nutritive value are poor in tropical forages, straws and stovers. Chemical treatments are expensive in developing countries and it may be more practical to supplement straws and stovers to optimise their utilisation. Alternatively, the introduction of varieties of superior nutritive value in straw or stover may provide a solution. Legumes may provide useful supplements to cover the nutrient deficiencies of many straws.

Legume fibre is superior to grass fibre: because of intrinsic compositional and structural factors it is consumed more readily and thus gives greater feed efficiency (Van Soest et al, 1984b). These intrinsic factors include rate of fermentation and buffering capacity (cation exchange) and, paradoxically, greater lignification. Tropical legumes are higher in protein and lower in fibre than their grass counterparts, and thus can serve as valuable supplements to straw- or stover-based rations.

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DISCUSSION

Thomson: Is it possible to adjust the amount of alkali added to crop residues to obtain optimal improvements in digestibility?

Van Soest: One approach would be to conduct a laboratory titration.

Jenkins: Could you explain the terminology associated with tannin effects on bacteria?

Van Soest: Tannins are defence compounds which react with protein, as in the leather reaction. Degraded tannins may have analogous effects on bacteria in the rumen.

Pearce: The role of silica in influencing nutritive value may not be so clear cut. Dr Juliano of IRRI has grown rice under hydroponic conditions with silica solutions of varying concentration. This did not influence rice straw digestibility.

Van Soest: The lignin content of straws may be important as it has been suggested that higher lignin contents occur in rice straw with lower silica contents, providing a compensatory effect. However there have been reports that silica does not limit straw digestibility under field conditions.

Ørskov: I have not found that silica affects rice straw feeding value.

Van Soest: Lignin is chemically different in legumes and grasses but degradability is the same. These differences disappear when results are expressed on a neutral-detergent fibre basis.

McAllan: You have suggested that phenolic compounds have tanning reactions with rumen bacteria. Could you explain that further?

Van Soest: The tannins react with nitrogenous compounds and form a polymer which becomes physically attached to bacteria. Condensed tannins are not digestible.

Uden: Can you explain how you separated out these indigestible compounds in the course of metabolic experiments?

Van Soest: This research was conducted *in vitro* and the optical density of the compounds was measured.

PHENOLICS IN FIBROUS CROP RESIDUES AND PLANTS AND THEIR EEFECTS ON THE DIGESTION AND UTILISATION OF CARBOHYDRATES AND PROTEINS IN RUMINANTS

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INTRODUCTION

Crop residues are important animal feeds in many developing countries. Up to 80% of their dry matter is cell-wall polysaccharides. The utilisation of this energy source depends on both the physical properties and the chemical composition of the residues. Although our knowledge of cell wall chemistry is still incomplete, it is known that phenolic compounds are an integral part of the hemicellulose fraction (Mueller-Harvey et al, 1986). Some tropical crop residues contain about 3% simple phenolic acids by weight. Other types of more complex phenolic compounds are known to be present in cereal grains (Ramachandra et al, 1977) and cereal crop residues (Jambunathan et al, 1986).

This review first presents the various classes of phenolic compound found in plants and current methods of analysis. The 'chemical defense' hypothesis is examined critically in the light of recent findings. The purported roles of phenolics in plants are presented before the interactions between phenolics and other cell constituents (carbohydrates and proteins) are reviewed. This is followed by discussion of the apparent effects of phenolic compounds on ruminant nutrition and rumen microbial metabolism. The review concludes by highlighting areas in which more information is required.

OCCURRENCE OF PHENOLICS IN PLANTS

Phenolics occur in several forms in plants: (1) as soluble compounds extractable with water (gallic acid esters) or with methanol and aqueous acetone (proanthocyanidins, flavonols, flavonolglycosides) and (2) in non-extractable forms. Phenolics may remain in the residue after extraction as a result of their inherent insolubility, e.g. due to their large molecular weights, or because they are covalently bonded to, or tightly bound in complexes with, other plant constituents (Beart et al, 1985b; Hartley and Buchan, 1979; Hartley and Keene, 1984; Mueller-Harvey et al, 1986).

CLASSES OF PHENOLIC COMPOUNDS

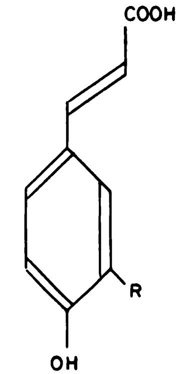
Structures

Several types of phenolic compound affect the digestion of crop residues, including simple phenolic compounds, such as the cinnamic acids (I) or aldehydes (II) and polyphenolics, such as the 'condensed' (III) and 'hydrolysable' tannins (IV) (Haslam, 1981) (Figure 1).

Polyphenolics

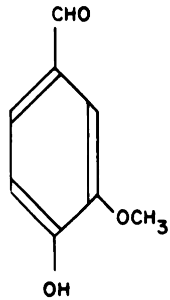
"Vegetable tannins" are a group of polyphenolics, consisting of a large number of structurally very different compounds. The original definition of a

Figure 1. *Structures of cinnamic acids (I), aldehydes (II) and condensed (III) and hydrolysable tannins (IV).*

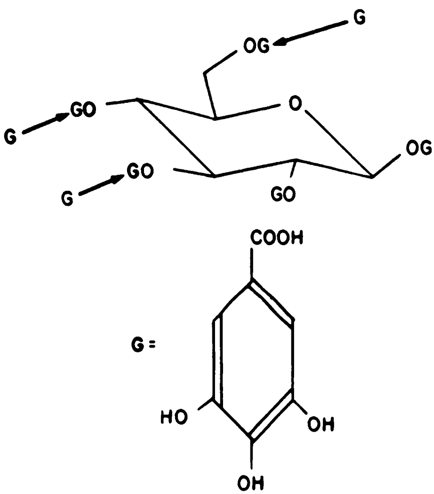


R = H or OCH_3

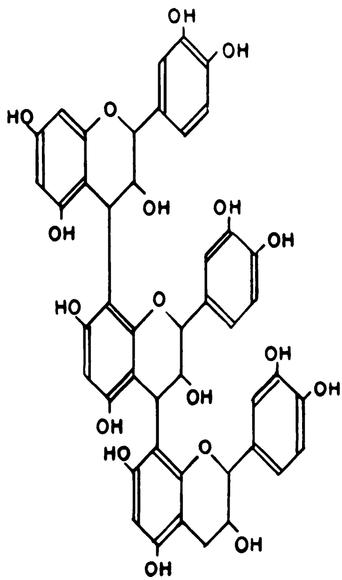
(I)



(II)



(IV)



(III)

"tannin" is a compound "able to convert hide to leather." All tannins contain phenolic groups, but not all phenolics are tannins. Many of these compounds have now been identified. It is increasingly obvious that even the modified definition of a tannin as "a compound that binds to proteins" (Swain and Bate-Smith, 1962) is imprecise and misleading and no longer serves any useful purpose. We will, therefore, try to avoid the word "tannin," except when referring to "condensed" and "hydrolysable tannins."

ANALYTICAL METHODS

Qualitative analysis

The literature on the effects of phenolics in animal nutrition has many examples of inappropriate use of analytical methods resulting in unsupported conclusions. This often stems from a poor understanding of the reactions between phenolic compounds and their detection agent. However, it may also frequently be a result of the use of unsuitable preparation procedures. Different types of phenolic have been estimated using unspecific methods. Quantification of phenolics is problematic because of the lack of a general standard compound, together with the likelihood that different phenolic compounds have different nutritional effects. This makes comparative assessments of nutritional responses extremely difficult.

Precautions need to be taken when extracting phenolics (McLeod, 1974; Gartlan et al, 1980). Many phenolic compounds isomerise in sunlight (*trans-cis* conversions; Kahnt, 1967), react with oxygen in alkaline solution (quinone formation) and with methanol at room temperature and pH 6 (Haslam, 1966).

Plant phenolics have been measured colorimetrically using the Folin-Denis reagent (Swain and Hillis, 1959). This reagent reacts non-stoichiometrically with phenolic and other OH groups, and several reducing agents interfere (Singleton and Rossi, 1965). Despite the lack of specificity for polyphenolics, this reagent has often been used to measure tannin content in forage crops because of its ease of use (Burns, 1963).

The Folin reagent as modified by Folin and Ciocalteau (1927) gives a better estimate of total phenolic groups (Single ton and Rossi, 1965). This reagent gives a greater colour response with phenols and a lesser response to non-phenolic compounds. Another general reagent for phenolic groups is Prussian blue (Price and Butler, 1977), but this has the disadvantage of a widely varying sensitivity for different compounds. Vanillin reacts under acidic conditions with one group of phenols, called flavanols. When used under the conditions recommended (Sarkar and Howarth, 1976) it is specific for a narrow range of flavanols (including condensed tannins) and dihydrochalcones (Swain and Hillis, 1959; Sarkar and Howarth, 1976).

Heating proanthocyanidins with hydrochloric acid and n- butanol produces strongly coloured anthocyanidins (Swain and Hillis, 1959). However, chlorophylls interfere and the reaction is not quantitative. The yield and type of anthocyanidins differ for each type of proanthocyanidin. Its advantage is its specificity.

Quantitative analysis

In order to assess the effects of phenolics in nutritional studies, quantitative estimates of the amounts present are required. Gallic acid (Singleton and Rossi, 1965), tannic acid (McLeod, 1974), catechin (Price et al, 1978) and chlorogenic acid (Walter and Purcell, 1979) have all been used as reference standards. However, tannic acid is a poor standard because it tends to be a mixture of different compounds, the relative proportions of which vary between samples (King and Pruden, 1970). Using catechin as a standard in the vanillin test over-estimates the concentration of condensed tannins because the reaction kinetics are different for the monomer and the oligomers (Price et al, 1978).

Gravimetric procedures (Tempel, 1982) have been used to obtain a direct measure of phenolics thus avoiding the problems associated with quantification in colorimetric assays. The hide powder assay (ALCA, 1956) measures the amount of phenolics adsorbed by the powder. However, Laurent (1975) found that results were variable and Verzele et al (1986) criticised the choice of hide powder because it selectively binds only some compounds from tannic acid mixtures.

Reed et al (1985) developed a method for precipitating soluble phenolics from plant extracts with ytterbium acetate. Precipitation was complete when phenolics accounted for more than 16% of the dry matter. The precipitates contained flavan-3-ols, condensed tannins, gallic acid and hydrolysable tannins, catechin gallates, flavonols and their glycosides (Mueller-Harvey, Reed and Hartley, unpublished data). Little protein or chlorophyll appeared to be co-precipitated with the phenolics. This method holds promise for the gravimetric determination of phenolic compounds and modifications are being made to obtain complete precipitation of all phenolics at lower concentrations.

High-performance liquid chromatography (HPLC) (Vande Casteele et al, 1982; Mueller-Harvey et al, 1987) is better able to distinguish among different types of phenolics but separations may be incomplete with complex mixtures of similar compounds, e.g. some mixtures of condensed and hydrolysable tannins.

THE ROLE OF PHENOLICS IN PLANTS AND IMPLICATIONS FOR BREEDING PROGRAMMES

The metabolic role of phenolics in the plant is still not clear. Feeny (1976) suggested that they serve as chemical defense agents through their astringent taste and by interfering with the digestive enzymes of the predators. Although a negative correlation was found between susceptibility to bird attack and polyphenolic content of sorghum grain (Bullard and Elias, 1980), Coley (1983) found no correlation between the extent of herbivore attack and phenolic content of mature leaves in a tropical forest. Similarly, Bernays (1981) stressed the variability of effects of polyphenolics on insect herbivores and warned against generalisation concerning their ecological significance.

A systematic approach by Beart et al (1985a) noted that the principal biosynthetic thrust in plants is towards the production of higher molecular weight polyphenolics which are the end-product of the metabolism. Based on the "defense hypothesis" one might assume that such end-prodcuts are produced by plants as these compounds are most effective in precipitating the proteins of the herbivores. Beart et al (1985a) therefore investigated the binding strength between various phenolic precursors and end-products with a protein, bovine serum albumin (BSA). To their surprise, they found that one common precursor, pentagalloyl glucose, bound the protein much more strongly than most of the end-products. This led them to doubt the defense hypothesis.

In a similar context in micro-organisms, Bu'Lock (1980) suggested that the secondary metabolism serves to maintain basic metabolism in circumstances not propitious for growth (e.g. nutritional imbalances). This is supported by the observation that the condensed tannin content of *Lotus* species was higher under low soil fertility than high soil fertility conditions (Barry and Forss, 1983) and that high phenolic contents have been linked with high light intensity, high temperatures and severe drought (Burns, 1966). A further example is that sainfoin grown in the UK had a much lower extractable phenolic content than sainfoin grown in Ethiopia (J.D. Reed, personal communication).

The basic principles of the metabolism of phenolics must be better understood in order to develop strategies for the development of plants with higher nutritive value. For example, if stress conditions cause more phenolic precursors to be synthesised and specific plant enzymes cause their polymerisation, two screening approaches could be employed:

1. To assess the effect of stress on precursor synthesis in different varieties; and

2. To assess the differences in plant enzymes which produce the polyphenolics.

This approach is supported by the fact that different types of precursor occur in different sorghum plants (Watterson and Butler, 1983), and by the discovery of different end products within the *Cinnamon* species (Nonaka et al, 1983). It should be possible to exploit such genetic differences in breeding programmes once the nutritional effects of the various phenolics are better understood.

MECHANISM OF PHENOLICS INTERACTION WITH CELL CONSTITUENTS AND THEIR DIGESTION

Carbohydrates and simple phenols

Several simple phenolics occur in plants. The derivatives of cinnamic acid are the most abundant; derivatives of benzoic acid and aldehydes occur in smaller amounts (Jung et al, 1983a; Hartley and Keene, 1984). Ferulic and p-coumaric acids are esterified to carbohydrates in plant cell walls (Mueller-Harvey et al, 1986), whereas the aldehydes are apparently linked at their phenolic groups to cell-wall polysaccharides (Hartley and Keene, 1984). It has been suggested that phenolic compounds limit the digestion of carbohydrates (Hartley and Jones, 1978): digestibility of cell-wall carbohydrates is increased when phenolic compounds are released from gramineaceous forages by treatment with alkali (Hartley and Jones, 1978).

Very little is known about the type of bonding between polyphenolics and carbohydrates. Beart et al (1985b) proposed that some proanthocyanidins may be covalently linked via ether bridges at C-4 to carbohydrates, in analogy to the C-C bridges in proanthocyanidins, but the evidence for such linkages is circumstantial. Other types of bonding between polyphenolics and carbohydrates have been demonstrated; H^+-bridges and hydrophobic interaction binding are important in such complexes.

Ford (1978) observed low digestibilities of cell walls from *Desmodium intortum* and suggested that this was probably caused by proanthocyanidins complexing with cellulose. More detailed studies showed that some condensed and hydrolysable tannins adsorb to starch (Davis and Hoseney, 1979). McManus et al (1985) studied binding among several polysaccharides and polyphenolics and concluded that the molecular size of the polyphenol and its conformational flexibility are important to the binding, which seems to be pH independent. They also noticed that small changes in the structure of either the polyphenol or the polysaccharide resulted in marked changes in their affinity for each other. Where the association was primarily a surface effect, broad similarities were noted with the analogous complexation with proteins. However, where the polysaccharide was also capable of forming inclusion complexes, significant differences were observed relative to the binding of proteins.

Proteins

The interaction between polyphenolics and proteins has been recognised for much longer than that with polysaccharides. However, we still do not understand the causes of the differences in the effects of polyphenolics among digestion trials. Polyphenolics have been reported to have both beneficial effects (Reed and Soller, 1987; McLeod, 1974) and detrimental effects (Reed and Soller, 1987; Reddy et al, 1985) on protein metabolism in ruminants.

The complexes formed by the interaction of proteins and phenolics in solution may be either soluble or insoluble (Van Buren and Robinson, 1969; Mole and Waterman, 1985). However, insoluble (non-extractable) phenolics can also complex proteins (Bate-Smith, 1977).

The effect of complex formation on the digestibility of proteins/phenolics and the activity of enzymes is not fully understood. Mole and Waterman (1985) reported that condensed tannins both stimulated and inhibited digestion of complexed proteins by trypsin. Although several enzymes are inhibited by polyphenolics (Butler et al, 1984 and references therein), others retain some or most of their activity whilst complexed (Goldstein and Swain, 1965; Davis and Hoseney, 1979). Thus, enzyme inhibition is not a good measure for so-called "tannins."

The formation of complexes depends on the concentration of both the polyphenolic and the protein, resulting in variable stoichiometries (e.g. ranging between 1:60 and 1:120 for the protein:polyphenol ratio) (McManus et al, 1981; Mole and Waterman, 1985). Precipitation is thought to occur when a hydrophobic outer layer is formed. Thus at appropriate concentrations even simple phenolics, such as pyrogallol and resorcinol, can precipitate proteins from solution (McManus et al, 1981). This example illustrates best why the term "tannin" is obsolete.

pH also affects precipitation (Jones and Mangan, 1977; Martin and Martin, 1983). Precipitation is greatest at a pH within one unit of the isoelectric point of the protein (Hagerman and Butler, 1978).

Martin et al (1985) demonstrated that metal ions influence the extent of precipitation between hydrolysable tannins and leaf fraction I protein: Mg^{2+} and Ca^{2+} were more effective than Na^+ and K^+ at bringing about protein precipitation.

Our present understanding of the mechanism of interaction favours both H^+-bond formation and hydrophobic interactions (Goldstein and Swain, 1965; Haslam, 1974; Oh et al, 1980).

As indicated earlier for carbohydrates, complex formation is dependent on both solution conditions and the properties of the phenolics and proteins. Molecular size and conformational flexibility have major effects on the strength of binding between polyphenol and protein. For example, molecular flexibility of certain ellagitannins is less than that of gallotannins due to intramolecular crosslinking: as a result, the ellagitannins bind BSA more weakly than do gallotannins (Beart et al, 1985a; McManus et al, 1985). Proteins with open, loose conformations interact much more strongly with sorghum polyphenolics (Asquith et al, 1987).

Thus, the great specificity of some polyphenolics for certain proteins (Becker and Martin, 1982; Butler et al, 1984; Asquith et al, 1987) can be likened to the specificity between enzymes and substrates. It follows that some proteins can be preferentially precipitated out of solution even in the presence of excess amounts of other proteins (Butler et al, 1984).

It seems reasonable to assume that the strength of binding in such complexes will have important implications on the degradability of complexes at different pH values (Jones and Mangan, 1977), by enzymes or micro-organisms (Martin and Martin, 1983).

Studies are also needed to assess any reactions within the polyphenol-protein complex that may occur during digestion. Beart et al (1985b) predicted that covalent bonds could be formed in such complexes in the ruminant.

EFFECT OF POLYPHENOLIC COMPOUNDS ON VOLUNTARY FEED INTAKE

Intake of feed containing large amounts of condensed tannins is low (Barry and Duncan, 1984). Barry and Duncan (1984) recorded an increase in both metabolisable energy intake (MEI) and digestible organic matter intake (DOMI) in sheep fed high-polyphenolic *Lotus* in response to decreasing condensed tannin content when polyethylene glycol (PEG) was used to bind the condensed tannins (Barry and Forss, 1983). Digestibilities of OM, cellulose, hemicellulose and nitrogen also increased. Thirty-two percent of the increase in DOMI could be attributed to increased intake of digestible fibre and a further 32% to increased intake of digestible crude protein. However, an increase in intake of digestible crude protein does not necessarily increase supply of amino acids to the animal, as shown by Thomson et al (1971) working with dried lucerne and sainfoin fed to sheep.

EFFECT OF POLYPHENOLICS ON THE SITES OF CARBOHYDRATE AND PROTEIN DIGESTION

The presence of condensed phenolics in sainfoin (Thomson et al, 1971; Egan and Ulyatt, 1980) and *Lotus* species (Barry et al, 1986b) has been associated with increased nitrogen retention in sheep. This has been attributed to an increased supply of amino acids to the small intestines as a result of protection of the plant protein from proteolysis in the rumen (Reid et al, 1974).

In *Lotus* species, condensed phenolic contents up to 25 g kg^{-1} DM appear to have little effect on rumen carbohydrate digestion but concentrations between 25 and 100 g kg^{-1} DM reduce carbohydrate digestion in the rumen in a dose-dependent manner (Barry and Manley, 1986; Barry et al, 1986b).

Barry and Manley (1986) found that, in *Lotus*-based feed, increased polyphenolic content significantly reduced the extent of digestion of OM in the rumen. The digestive behaviour of the high-polyphenolic *Lotus* was compared with the predicted behaviour of the same crop assuming it was a low-polyphenolic crop. The predicted increased flow of organic matter (measured as the sum of its individual components) was 99 g d^{-1}, of which 42% was fibre and the remainder largely crude protein. This supported the suggestion by Barry and Duncan (1984) that polyphenolics both reduce digestion of carbohydrates in the rumen and increase protein outflow. The amount of fibre excreted in the faeces was equal to the amount of extra fibre entering the small intestine suggesting that dietary fibre not digested in the rumen was irreversibly bound by polyphenolics. In contrast, approximately 60% of the extra protein entering the duodenum was digested in the small or large intestine. However, in further similar experiments Barry et al (1986b) found that the reduction in carbohydrate digestion in the rumen was compensated by increased post-ruminal digestion and whole tract digestibility appeared unaffected.

In another study, Thomson et al (1971) examined the digestion of dried sainfoin (high condensed tannin) and lucerne (low condensed tannin) in mature sheep. Although the crops were harvested at similar stages of growth and had similar total N contents, cellulose digestibility was significantly higher on sainfoin (78 vs 67) and the extent of cellulose digestion in the rumen was unaffected. In contrast, apparent N digestibility was significantly lower in sainfoin (68 vs 51). However, duodenal amino acid supply from sainfoin was 49% greater (178 vs 119 g d^{-1}) and, despite a small increase in total amino acid flow at the ileum (sainfoin 64, lucerne 52 g d^{-1}), availability of amino acids in the small intestine was 46 g d^{-1} greater from sainfoin than from lucerne. This response was seen despite a significant reduction in apparent N digestibility (whole tract) and indicates (a) the futility of using apparent N digestibility as a measure of protein value, and (b) a marked positive effect of condensed tannins on protein supply to the host animal.

In this study, no real attempts were made to determine the origin of duodenal protein on the two diets, but in a parallel publication Harrison et al (1973), using DAPA, reported that bacterial N contributed 37% (sainfoin) and 79% (lucerne) to total duodenal N, suggesting that undegraded dietary protein made a major contribution to the overall increased protein flow on sainfoin. Irrespective of its origins, the apparent availability of amino acids in the small intestine appeared to be unaffected by the presence or absence of tannins.

In a subsequent study, Beever and Siddons (1985) examined the effect of sainfoin tannins on 'protein protection' in the rumen, and the possible effect of a small proportion of sainfoin on the digestion of a tannin-free legume such as red clover.

All diets had similar total N contents, but soluble N contents were noticeably lower on the sainfoin-rich diets (Table 1). Duodenal amino acid flows were less than amino acid intake (as expected on fresh forages), but were 11-28% higher on the sainfoin diet than on all other diets (Table 2). Similarly, the flow of microbial protein was highest on the sainfoin diet and it was concluded that much of the increased duodenal

Table 1. Nitrogenous fractions of diets containing varying proportions of sainfoin and red clover.

Percentage contribution (DM basis)				
Sainfoin	100	40	20	0
Red clover	0	60	80	100
Dietary characteristics (g kg^{-1} DM)				
Total N	34	37	38	38
Rumen liquor TCA soluble N	12	18	21	22
Buffer soluble N	8	11	14	15

Source: Beever and Siddons (1985).

Table 2. Duodenal digesta amino acids flows and efficiencies of microbial synthesis in sheep receiving diets containing varying proportions of sainfoin and red clover.

Percentage contribution (DM basis)				
Sainfoin	100	40	20	0
Red clover	0	60	80	100
Duodenal amino acid flow (g g^{-1} intake)				
Total	0.83	0.65	0.75	0.67
Microbial	0.41	0.33	0.35	0.32
Feed	0.32	0.25	0.32	0.28
Microbial synthesis (g g^{-1} degraded amino acid)				
	0.61	0.44	0.51	0.44

Source: Beever and Siddons (1985).

amino acid was due to increased microbial synthesis. This contrasts with the findings of Harrison et al (1973), but in their study the diets were artificially dehydrated prior to feeding. Of possibly greater consequence, however, is that there was no positive interaction between sainfoin and red clover, from which it may be concluded that the polyphenolics of sainfoin are specific (both physically and chemically) to sainfoin protein or that they were not present in sufficient quantity to exert any real effect on the red clover proteins.

The effects of condensed tannins on carbohydrate digestion have been attributed, at least in part, to complexing of microbial extracellular enzymes. Condensed tannins inhibit *in vitro* proteolytic, cellulolytic and general fermentative activities of rumen microbes (Schaffert et al, 1974; Tagari et al, 1965) and *in vivo* microbial multiplication (Sadanandan and Arora, 1979).

No information appears to be available on the effects of condensed tannins on protozoal or fungal fermentative capacities, both of which may contribute considerably to digestion of structural carbohydrates. However, the reduction in rumen digestibility in animals receiving diets high in condensed tannins may simply reflect insufficient rumen-degradable nitrogen (RDN) for maximum microbial activity. This is supported to some extent by the responses of rumen digestion to additional non-protein nitrogen. Adding 3% urea to a diet of wheat straw and deoiled sal seed meal fed to calves increased total nutrient digestibility from 48 to 61% (Sinha and Nath, 1982). Similar effects were observed *in vitro* where adding urea to high- and low-condensed-tannin sorghum grains increased *in vitro* dry matter digestibility (IVDMD) from 73 to 93% in low-condensed-tannin cultivars and from 46 to 79% in high-condensed-tannin cultivars (Schaffert et al, 1974).

It is not known whether urea destabilises the bonding between protein and condensed tannins, releasing protein for microbial use, or if the urea simply acts as a source of RDN. The latter would seem to be more probable: Schaffert et al (1974) observed no effect of urea on *in vitro* protein degradabilities of sorghum grains despite increased IVDMD. *In vivo* studies also tend to support the idea that lack of RDN reduces digestion. Egan and Ulyatt (1980) associated the higher N retention in sheep receiving sainfoin than in those receiving clover or ryegrass diets with an increased rate of recycling of nitrogen (presumably as urea) into the rumen. Barry et al (1986b) reported rumen ammonia levels of about 16 mM in sheep receiving *Lotus* diets containing 95 g condensed tannins per kg DM and Reed and Soller (1987) found that sheep receiving acacia browse, which is high in condensed tannins, excreted significantly less nitrogen in the urine than sheep receiving *Sesbania sesban* or vetch hay, which are low in condensed tannins. The latter authors suggested that changes in urinary nitrogen excretion could be the result of increased microbial utilisation of endogenous nitrogen in the rumen.

Digestibility of structural carbohydrates in the rumen is greater with protein supplementation than with NPN (urea) supplementation and responses to different protein sources differ (McAllan and Smith, 1983). However, supplementing diets containing large amounts of condensed tannins with protein may not be economical and other ways to reduce the adverse effects of phenolics must be explored.

Other studies on nitrogen utilisation of feeds high in phenolic contents have shown both positive and negative effects (Reed and Soller, 1987), indicating the need for caution in extrapolating reported effects of phenolics on digestion or utilisation parameters from one plant to another. Reed et al (1985) examined the effects of phenolic compounds from a variety of plants in an *in vitro* cellulase system and found that the degree of inhibition varied from about 2 to 70%: this variation was probably related to the types and amounts of phenolic compounds present. Other workers have also reported markedly different responses in rumen microbial activity to phenolics from different sources (Tagari et al, 1965).

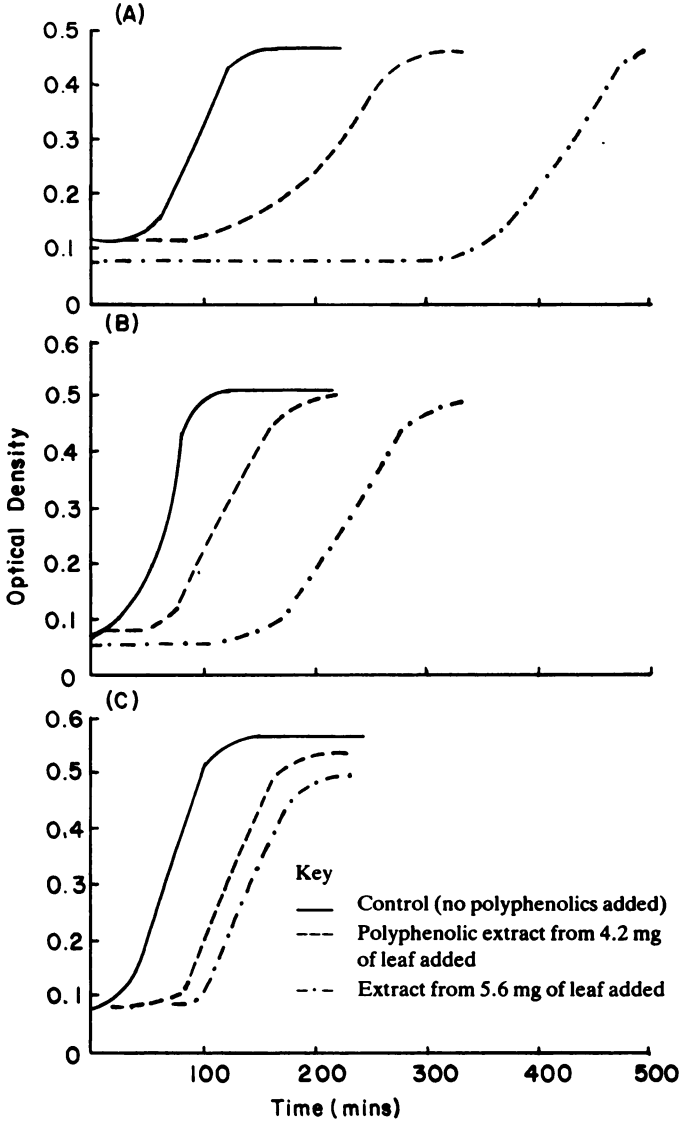
EFFECTS OF PLANT PHENOLICS ON RUMEN MICROBIAL ACTIVITY

Recent experiments (Mueller-Harvey, Theodorou, Hitchin, Dhanoa, unpublished data) assessed the anti-microbial and physiological effects of several types of polyphenolic compound from Ethiopian browse plants on *Streptococcus bovis*. In general, all extracts increased lag times and reduced biomass yields. Growth rates were also reduced, but only in cultures grown with insufficient organic nitrogen. Large differences were observed in the extent of these anti-microbial effects when comparable concentrations of phenolics from *Acacia nilotica, Euclea schimperi* and *Pterolobium stellatum* were added to *S. bovis* cultures. Extracts from *A. nilotica* were substantially more toxic, confirming that polyphenolics are not a uniform group of chemicals having similar effects.

The effect of polyphenolics on *S. bovis* was reduced by increasing the organic nitrogen concentration in the culture medium (Figure 2). Other workers have also reported markedly different responses in rumen microbial activity to polyphenolics from different plant sources (Tagari et al, 1965).

The toxicity of free phenolic acids has been demonstrated in a wide range of rumen bacteria (Chesson et al, 1982). Bacteriocidal and bacteriostatic effects have been demonstrated in cellulolytic bacteria, such as *Ruminococcus albus, R. flavifaciens* and *Bacteroides succinogenes*, in the presence of 10mM or less of p-coumaric acid and ferulic acid (Chesson et al, 1982). Akin (1982) also observed that cellulolytic and xylanolytic bacteria were inhibited by p-coumaric acid and

Figure 2. *Effect of polyphenolics from* Acacia nilotica *on the growth of* Streptococcus bovis *at different concentrations of organic nitrogen. Cultures were grown on glucose in medium B (Lowe et al, 1985). A: no organic nitrogen (yeast extract and trypticase omitted). B: half the amount of yeast extract and trypticase. C: full amount of yeast extract and trypticase.*



ferulic acid and that p-coumaric acid reduced motility in entodinomorph, but not holotrich, protozoa. Ferulic acid and sinapic acid had lesser effects on protozoa (Akin, 1982).

Vanillin and, to a lesser extent, cinnamic acid also inhibit cellulolysis by rumen bacteria, apparently by preventing them from attaching to cellulose particles. Similar observations have been reported by Akin et al (in press). Differences in responses to phenolic acids may reflect the dominant bacterial species in the rumen, because individual species of rumen cellulolytic bacteria are affected differently by a given phenolic acid (Chesson et al, 1982). Akin et al (in press) reported changes in sub-group populations, from ruminococcus-like to bacteroides-like morphotypes, in the presence of phenolic acids. Some adaptation by bacteria can occur (Akin et al, in press) and changes in the proportions of VFAs produced over extended incubation periods indicate possible changes in the microbial population.

The effect of phenolic acids on fibre digestion by mixed populations of rumen microorganisms is less clear. Jung and Fahey (1983) reported that a range of phenolic acids, including p-coumaric acid, ferulic acid, protochatecuic acid and vanillin, have a negative effect on the extent of *in vitro* cellulose digestion but the concentrations required to cause inhibition were in excess of those normally encountered in the rumen. Degradation of forage cell walls by rumen microorganisms alters the amounts of phenolic acids recoverable from plant materials (Theander et al, 1981). Several reports have presented evidence for the breakdown or modification of free monomeric phenolic acids or more complex phenolics under strictly anaerobic conditions (e.g. Chen et al, 1985). In general, microbial consortia are required to modify these phenolics, although some pure cultures of rumen bacteria degrade phenolics, with a greater apparent degradation of ferulic than coumaric acid (Theander et al, 1981). Low recoveries of phenolic acids added to *in vitro* incubations have also been observed by a number of workers (Chesson et al, 1983; Jung and Fahey, 1983; Jung et al, 1983a).

Since cellulolytic bacteria are closely associated with structural polysaccharides in the rumen (Akin, 1976) they may encounter locally high concentrations of potentially toxic bound and free phenolic acids as degradation proceeds. No obvious relationship was found between depressions of cellulose and hemicellulose digestibilities and changes in substitutions to the aromatic ring of the phenolics although aldehydes were found to be more inhibitory than related acids (Jung, 1985). Hemicellulolytic bacteria appear to be more tolerant of phenolic acids than cellulolytic bacteria (Jung, 1985), presumably because these phenolics are linked to the hemicellulose fraction of the cell walls and hemicellulolytic bacteria are adapted to these phenolics.

Experiments with some forages have shown a negative correlation between the phenolic constituents of cell walls and apparent digestibility (Hartley, 1972); removal of phenolic acids from cell walls increases digestibility (Chesson, 1981; Hartley and Jones, 1978; Jung and Fahey, 1981). Ford and Elliott (1987), however, found no relationship between the concentration of any cell-wall constituent and degradability. These latter authors suggested that variability in biodegradability of cell walls is more probably a result of structural features such as crosslinking between polymers than concentration of any particular cell-wall constituent.

EFFECT OF POLYPHENOLICS ON ANIMAL PERFORMANCE

Barry et al (1986a) examined the effects of tannins on nutrient utilisation in sheep fed high-condensed-tannin *Lotus*. They observed increased levels of growth hormone and their results suggested an increase in the ratio of lipolysis to lipogenesis. Similar trends were reported by Purchas and Keogh (1984), who found lower carcass fat levels in lambs grazing *Lotus* than in those grazing white clover. This could be due to dilution of fat content by increased N retention, while increased lipolysis may have been mediated by increased secretion of growth hormone.

CONCLUSION

Plant phenolics are a diverse group of chemicals. Each group can have different effects on the nutritive value of plants for feeding ruminants. Polyphenolics are very reactive and precautions are needed to avoid reactions during handling that affect quantitative and qualitative analysis. The choice of methods for phenolic analysis is difficult and requires consideration of the specificity of each method.

There is sufficient information to question the hypothesis that plants produce polyphenolics in order to defend themselves against insect and herbivore attack (the "chemical defense hypothesis"). An alternative hypothesis is that plants produce phenolics in response to stress conditions such as low soil fertility, drought, high temperature, high light intensity and grazing pressure. This hypothesis needs testing by plant physiologists.

A proper understanding of the metabolism of phenolics is needed to assist plant breeding programmes. The variability in enzymatic pathways that lead to the production of phenolic precursors and end-products needs to be investigated. The differences between phenolic compounds which have positive effects on ruminant nutrition and those which have negative effects need to be determined. The difference may depend on the chemical structure of the phenolic and the specificity of the interaction of the phenolics with proteins and carbohydrates.

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DISCUSSION

Jenkins: Could you clarify whether phenolics are produced under stress or do they provide protection under stress conditions?

Mueller-Harvey: Under stress conditions normal metabolism is affected and light energy which would be converted to carbohydrate has to be absorbed in another way. The plant responds by producing phenolics.

Van Soest: Lignin production decreases under stress conditions but tannin levels increase. In alfalfa isoflavones are produced.

Reed: If stovers are sun-dried the phenolics may polymerise and thus have a lower inhibitory effect on bacteria. However, in the process of polymerisation some nutrients may be complexed and they become less available.

Aboud: If phenolics are produced in response to stress conditions, why do plants such as tea contain substantial amounts of tannins?

Mueller-Harvey: Some plants routinely produce phenolic compounds.

PRACTICAL PROBLEMS OF FEEDING CROP RESIDUES

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INTRODUCTION

The vast amount of crop residues/fibrous byproducts available as potential ruminant feed--some 2.0 t DM per 500 kg livestock unit annually in developing countries (Kossila, 1984)--is now generally acknowledged. With the world population predicted to double by 2025 (even treble in the developing tropics), cereal production, and hence straw production, will have to increase. With the increased pressure on land for food production, less land will be available to produce animal feed, either from pasture or fodder crops, and crop residues will assume even greater importance as animal feed. This will lead to greater integration of crop and animal (mainly ruminant) production (Gartner, 1984).

The importance of small ruminants (especially goats) in developing-country agriculture is now widely recognised (Devendra and Burns, 1983; World Bank and Winrock International, 1983; Timon and Hanrahan, 1986). It is less well recognised, however, that small ruminants are mainly associated with small-scale farmers and that small-scale farmers predominate in developing-country agriculture. It will be these farmers who will need to practise crop-animal integration. A major constraint to crop-livestock integration is the potential damage to food crops from indiscriminate grazing, especially by goats. Owen et al (in press) stressed the need to research and develop stall-feeding systems for small ruminants based on crop byproducts.

Much has been written in recent years about the potential of crop residues as ruminant feed and about ways of overcoming their low nutritive value by upgrading and supplementing (e.g. Sundstøl and Owen, 1984; Doyle et al, 1986a). Much less effort has been put into identifying the factors limiting greater usage of crop residues and new technology, particularly by small-scale farmers in developing countries (Owen, 1985).

With the latter target-group in mind this paper will therefore briefly identify constraints which occur in the post-harvest period, as well as practical problems of feeding crop residues. The results of experiments recently undertaken with goats and sheep at Reading will be used to demonstrate how the amount of barley straw offered can affect the quantity and quality of straw consumed. The implications of this in regard to supplementation, plant breeding and developing strategies for feeding crop residues will be discussed, and areas needing further research will be identified.

POST-HARVEST AND PRE-FEEDING CONSTRAINTS

Decisions on whether or not to conserve crop residues for feed have to be taken soon after harvesting and often long before feeding them. Lack of convincing economic evidence in favour of their greater use as feed is undoubtedly a restraining factor (Edelsten and Lijongwa, 1981; Giaever, 1984; Tambi, in press). Animal scientists are partly to blame in that they have generally emphasised biological rather than economic responses to upgrading and supplementing crop residues. A problem which has a bearing on this is the difficulty of accurately predicting the nutritive (and therefore economic) value of crop residues from simple laboratory techniques, as evidenced by the recent EEC workshop (Chenost, in press). The problem is likely to be even greater for tropical crop residues containing anti-nutritional phenolic compounds (Mueller-Harvey et al, 1987), especially if feeding systems allow the animals to exercise selective feeding.

Cereal straws/stovers generally either are left in the field or accumulate where the crop is threshed. This is often far from where animals are kept and either the animals must be brought to the field for stubble grazing, or crop residues have to be transported to the animals. The bulk of straws and stovers and lack of transport discourage greater use of straws and stovers as feed. Transporting crop residues, even over short distances, may be uneconomic for small farmers (Mlay, 1987).

The handling and storing of crop residues have been discussed by Hilmersen et al (1984). More research and development is required to alleviate problems associated with storage of crop residues. These include risk of loss due to fire, and reduction in nutritive value due to moulding (especially in humid conditions) and damage by vermin and insects. Straws and stovers comprise stem and leaf plus leaf sheath (approximately 1:1 in barley straw), and harvesting, handling and storing systems should minimise the loss of the more nutritious leaf and leaf sheath. In this regard delayed harvesting, or relay harvesting in an intercropped field, would be expected to cause greater loss of leaf and leaf sheath, with a consequent reduction in nutritive value.

BACKGROUND TO THE READING EXPERIMENTS--
THE GRAZING APPROACH

Crop residues are characteristically low in metabolisable energy and nitrogen content and thus intake is low. Methods of upgrading straws as feed are well documented (Sundstøl and Owen, 1984) and guidelines on researching the subject are available (Preston et al, 1985). There has been more emphasis on upgrading straws for cattle than for sheep (Greenhalgh, 1984) but goats have received little attention (Owen, 1981; Owen and Kategile, 1984). Upgrading straws for feed is regarded as inappropriate for developing countries, especially for small-scale farmers, because it is expensive and needs technical expertise. Greenhalgh (1984) concluded that in many situations chemical upgrading will be superceded by breeding more nutritious straw, improved harvesting methods and judicious supplementation. The Reading experiments reported here suggest another approach, namely increasing intake of digestible nutrients and therefore animal productivity from crop residues by allowing selective feeding by goats and sheep.

The literature on feeding straws to sheep and goats involves experiments where intake and digestibility have been measured under *ad libitum* feeding. *'Ad libitum'* is defined as offering sufficient feed (usually in chopped form) to ensure that 15 to 20% is left (refused) by the end of the feeding period (Blaxter et al, 1961). This approach is standard and has the advantage (for the experimenter, but not the animal) of minimising selective feeding. We would argue that the latter is a disadvantage. The selective grazing and browsing behaviour of sheep (Gibb and Treacher, 1976) and goats (McCammon-Feldman et al,

1981) is recognised. Indeed, experiments (e.g. Gibb and Treacher, 1976) indicate that maximum intake by grazing sheep is achieved only if the herbage allowed exceeds intake by 400%. We therefore hypothesised that conventional *ad libitum* straw feeding would restrict intake by reducing the opportunity for animals to select better quality material.

This hypothesis was tested in the experiments reported. The experiments are also aimed at helping us develop strategies for stall-feeding straw to goats and sheep.

MATERIALS AND METHODS

Seven experiments conducted at Reading during the past 5 years are presented. All measured straw intake and assessed the degree of selective feeding by careful sampling and analysis of feed offered and refused. Except in Experiment 1 (no concentrate fed), the animals were fed a concentrate supplement (sugar-beet pulp, 600 g kg^{-1}; soya bean meal, 180 g kg^{-1}; fish meal, 180 g kg^{-1}; minerals and vitamins, 40g kg^{-1}) at 15 g DM kg^{-1} $W^{0.75}$ d^{-1} to satisfy nitrogen, mineral and vitamin requirements (ARC, 1980) for maintenance and modest growth in sheep. Numbers of animals used, type and mean weight are shown in Tables 1 to 7. All experiments used housed (16 hours light, 8 hours dark), individually penned castrated animals bedded on sawdust and provided with water. In Experiment 6 goats were in metabolism cages and faeces were collected over 9 days following a preliminary period of 14 days. In all other experiments preliminary periods were of 14 to 21 days and experimental periods lasted 21 days, except for Experiment 4 (42 days). Feeds were offered (in large feed boxes) twice daily and straw refusals carefully collected daily. Representative samples (based on aliquots) of straw offered and refused were taken daily and pooled samples were analysed (Wahed and Owen, 1986a) for dry matter, ash and nitrogen (AOAC, 1975), acid detergent fibre (Goering and Van Soest, 1970) and *in vitro* digestibility (Tilley and Terry, 1963).

RESULTS

Experiment 1

Experiment 1 (Table 1) examined whether any of the claimed superiority of goats over sheep, in regard to roughage intake and digestion, could be attributed to differences in feed selected under stall-feeding. The straw fed was treated with aqueous ammonia using a stack method (Sundstøl and Coxworth, 1984). The experiment showed goats to eat more than sheep, but there was no large difference between the quality of straw refused by the two species. It was clear, however, that both species were feeding selectively. Refused straw was of lower nutritive value than that offered.

Experiment 2

Experiment 2 (Table 2) was the first trial to test the hypothesis outlined earlier. Allowing goats to refuse 50% of the straw offered increased DM intake by 31% compared with the more conventional 20% refusal rate. The quality of feed refused indicated that goats allowed the higher refusal rate selected more nutritious straw. Thus the estimated intake of straw digestible OM (based on *in vitro* digestibility) was 40% higher. The 18

Table 1. Intake and selection of NH_3-treated barley straw by sheep and goats (Experiment 1).

			Suffolk-cross mule wethers	Saanen castrate goats	SED
Number of animals			8	8	
Liveweight (W) (kg)			57.9	50.7	9.0
Straw intake					
Offered[1] ($g\ DM\ d^{-1}$)			1299	1477	
Intake ($g\ DM\ d^{-1}$)			956	1117	152.4
($g\ DM\ kg^{-1}\ W\ d^{-1}$)			16.4	21.6	1.5
Chemical composition	Straw offered	SE	Straw refused		
Nitrogen ($g\ kg^{-1}$ DM)	17	0.5	11.6	12.2	0.6
Acid-detergent fibre (ADF) ($g\ kg^{-1}$ DM)	567	5.7	612	600	6.4
In vitro digestibility[2] (DOMD) ($g\ OM\ kg^{-1}$ DM)	607	6.0	544	566	

1. To allow a refusal rate of 20 to 25% of amount offered.
2. Tilley and Terry (1963).
Source: Wahed and Owen (1986a).

goats used per treatment represented a wide range of liveweight (15 to 65 kg), and small goats tended to be more selective than larger ones.

Experiment 3

In Experiment 3 (Table 3) increasing the refusal rate allowance increased intake of both long and chopped straw. The trend (non-significant) was for greater intake of long straw. Straw-length interacted significantly with refusal rate for refusal digestibility, indicating easier selective feeding with long than with chopped straw. All

Table 2. **Effect of allowing two rates of refusal on intake and selection of barley straw by goats (Experiment 2).**

			Straw refusal allowance 20%	Straw refusal allowance 50%	SED
Number of goats[1]			18	18	
Straw intake[2] (g DM kg^{-1} W d^{-1})			14.4	18.9	0.70
Straw intake (g DM kg^{-1} $W^{0.75}$ d^{-1})			33.1	43.7	1.60
Straw refused (% of offered)			20.5	48.3	
Estimated intake of straw digestible OM[3] (g kg^{-1} W d^{-1})			5.9	8.3	
Chemical composition	**Straw offered**	**SE**	**Straw refused**		
Nitrogen (g kg^{-1} DM)	5.1	0.02	4.5	4.6	0.13
ADF (g kg^{-1} DM)	552	7.0	612	596	4.8
In vitro DOMD[4] (g OM kg^{-1} DM)	412	4.8	320	347	7.7

1. Mean liveweight 32.6 kg.
2. Concentrate supplement also fed at 15 g DM kg^{-1} $W^{0.75}$ d^{-1}.
3. Calculated from *in vitro* digestibility of straw offered and refused.
4. Tilley and Terry (1963).

Source: Wahed and Owen (1986b).

subsequent experiments were therefore carried out with long straw.

Experiments 4 and 5

Experiment 4 (Table 4) simulated the 'grazing approach' (Gibb and Treacher, 1976) in that the amount of straw offered was based on goat weight and not so as to achieve a target rate of refusal. The results, however, corroborated those of Experiments 2 and 3. They also showed (not unexpected-

Table 3. Effect of chopping the straw on the response of goats to increasing refusal-rate allowance (Experiment 3).

Treatment[1]	Refusal rate main effect		Straw length main effect		SED main effect	Refusal rate x straw length interaction
	20%	50%	Long	Chopped[2]		
Number of goats[3]	16	16	16	16		
Straw intake (g DM kg^{-1} W d^{-1})	13.1	18.0	16.5	14.7	1.71	NS
Straw refused (% of offered)	19.4	49.1	39.3	40.8		
Composition of refused straw						
Nitrogen (g kg^{-1} DM)	4.9	5.0	4.7	5.2	0.22	NS
ADF (g kg^{-1} DM)	583	582	608	557	5.64	NS
In vitro DOMD[4] (g OM kg^{-1} DM)	343	371	326	388	1.20	P<0.05[a]

1. Design: 2x2 factorial, 8 replicates.
2. Using a precision-chop forage harvester.
3. Mean liveweight 30.5 kg.
4. Tilley and Terry (1963).
a. Difference between long and chopped greater with 20% refusal rate.
Source: Wahed (1987).

ly) that intake response diminished with increasing allowance rate, particularly for estimated digestible OM intake. Experiment 5 (Table 5) with sheep showed similar results.

Experiment 6

Experiment 6 (Table 6) investigated the feasibility of refeeding 'stall-grazed straw', as such or after treatment with ammonia (stack method; Sundstøl and Coxworth, 1984). Intake of untreated stall-grazed straw (straw-previously-refused) was significantly less than that of the original straw, but intake of digestible OM (measured *in vivo*) of the treated stall-grazed straw was the same as that with the original, untreated straw.

Table 4. **Effect of amount offered on intake and selection of barley straw by goats (Experiment 4).**

			Straw offered (g DM kg^{-1} W d^{-1})			
			18	54	90	SED
Number of goats			12	12	12	
Initial (day 1) liveweight (kg)			30.2	30.6	30.4	0.56
Final (day 42) liveweight (kg)			30.1	33.1	34.0	0.71
Straw intake[1] (g DM kg^{-1} W d^{-1})			15.5	22.8	26.2	0.74
Straw intake (g DM kg^{-1} $W^{0.75}$ d^{-1})			36.0	54.2	62.3	1.73
Straw refused (% of offered)			12.5	56.6	70.3	
Estimated intake of straw digestible OM[2] (g kg^{-1} W d^{-1})			7.2	12.8	14.5	
Chemical composition	Straw offered	SE	Straw refused			
Nitrogen (g kg^{-1} DM)	7.4	0.12	5.5	5.7	6.1	0.11
ADF (g kg^{-1} DM)	528	2.0	565	583	574	6.9
In vitro DOMD[3] (g OM kg^{-1} DM)	443	4.5	354	370	403	14.5

1. Concentrate supplement also fed at 15 g DM kg^{-1} $W^{0.75}$ d^{-1}.
2. Calculated from *in vitro* digestibility of straw offered and refused.
3. Tilley and Terry (1963).

Source: Wahed and Owen (1986b).

Experiment 7

Experiment 7 (Table 7) was only recently completed and aimed to assess whether intake and selection response to increasing refusal allowance would be affected by treating the straw with sodium hydroxide (dip method; Sundstøl, 1981). The preliminary results are somewhat surprising, indicating no apparent increase in straw DM intake due to increasing the refusal allowance. There was a sig-

Table 5. Effect of amount offered on intake and selection of barley straw by sheep (Experiment 5).

			Straw offered ($g\ DM\ kg^{-1}\ W\ d^{-1}$)			
			18	54	90	SED
Number of wethers[1]			10	10	10	
Straw intake[2] ($g\ DM\ kg^{-1}\ W\ d^{-1}$)			14.1	19.0	22.2	0.81
Estimated digestibility of straw consumed[3] ($g\ OM\ kg^{-1}\ DM$)			467	562	572	
Straw refused (% of offered)			20.8	64.7	75.1	
Chemical composition	Straw offered	SE	Straw refused			
Nitrogen ($g\ kg^{-1}\ DM$)	6.4	0.2	4.5	5.1	5.5	0.12
ADF ($g\ kg^{-1}\ DM$)	542	7.9	610	581	564	8.4
In vitro DOMD[3] ($g\ OM\ kg^{-1}\ DM$)	432	0.8	294	361	374	7.2

1. Mean liveweight 52.8 kg.
2. Concentrate supplement also fed at 15 g DM $kg^{-1}\ W^{0.75}\ d^{-1}$.
3. Calculated from *in vitro* digestibility of straw offered and refused.
4. Tilley and Terry (1963).

Source: Naate (1986).

nificant increase in DM intake in response to NaOH treatment. In this experiment samples of straw offered and refused were botanically fractionated (Ramazin et al, 1986), and the results (Table 7) indicate that generous feeding (allowing high refusals) increased intake of leaf plus sheath and reduced intake of stem. As expected with barley straw (Ramazin et al, 1986), the leaf plus sheath fraction was of higher nutritive value than the stem fraction (Table 8).

Table 6. Digestible straw intake by goats fed straw of straw-previously-refused, with or without ammonia treatment (Experiment 6).

	Straw[1]		Straw-previously-refused by goats[2]		
	Un-treated	NH_3-treated	Un-treated	NH_3-treated	SED
Number of goats[3]	6	6	6	6	
Straw intake					
g DM kg^{-1} W d^{-1}	22.8	24.5	15.8	19.4	1.98
g DM kg^{-1} $W^{0.75}$ d^{-1}	53.9	58.9	37.5	47.3	4.71
g digestible OM[4] kg^{-1} W d^{-1}	9.7	12.6	6.6	9.7	0.90
g digestible OM kg^{-1} $W^{0.75}$ d^{-1}	22.9	30.4	15.6	23.7	2.11

1. Barley straw fed in Experiments 2 and 4; fed to allow 50% rate of refusal; straw chopped. Concentrate supplement also fed at 15 g DM kg^{-1} $W^{0.75}$ d^{-1}.
2. Straw from 50% refusal rates in Experiments 2 and 4; straw chopped. Concentrate supplement also fed at 15 g DM kg^{-1} $W^{0.75}$ d^{-1}.
3. Mean liveweight 36.0 kg.
4. *In vivo* digestibility measured; concentrate OMD assumed to be 80%.

Source: Wahed and Owen (1987).

DISCUSSION

The above results clearly support the hypothesis that goats and sheep will consume more barley straw if they are permitted to reject 50% of that offered, rather than the conventional 10 to 20%. Furthermore, the improvement in consumption of digestible straw is even greater because generous feeding allows animals to select the more digestible fractions (leaf rather than stem).

These findings need to be corroborated with *in vivo* measurements of digestible straw intake

Table 7. Effect of refusal rate and NaOH treatment of barley straw on intake and selection by goats (Experiment 7).

	Untreated		NaOH-treated	
Straw refusal allowance (% of offered):	20	50	20	50
Number of goats[1]	9	9	9	9
Straw offered[2]				
Amount (g DM d^{-1})	805	1398	1031	1807
Leaf plus leaf sheath (g kg^{-1} straw DM)	449	449	451	451
Stem (g kg^{-1} straw DM)	477	477	502	502
Straw refused				
Amount (g DM d^{-1})	166	758	197	933
Leaf plus leaf sheath (g kg^{-1} straw DM)	307	359	355	405
Stem (g kg^{-1} straw DM)	661	613	612	559
Straw consumed				
Total (g DM kg^{-1} W d^{-1})	16.5	16.7	19.8	20.0
Leaf plus leaf sheath (g DM kg^{-1} W d^{-1})	6.6	10.6	7.1	11.2
Stem (g DM kg^{-1} W d^{-1})	7.1	5.3	9.4	8.8

1. Saanen castrates, mean liveweight 41.1 kg.
2. Concentrate supplement also fed at 18 g DM kg^{-1} $W^{0.75}$ d^{-1}.

Source: E Owen, R Alimon and W El-Naiem (unpublished data).

Table 8. Composition of straw offered in Experiment 7.

	Untreated straw		NaOH-treated straw	
	Leaf + leaf sheath	Stem	Leaf + leaf sheath	Stem
Ash (g kg^{-1} DM)	28.0	22.0	72.0	44.8
Na (g kg^{-1} DM)	1.7	1.2	21.1	14.5
ADF (g kg^{-1} DM)	512	668	501	610
In vitro DOMD[1] (g OM kg^{-1} DM)	515	262	664	367

1. Tilley and Terry (1963).

and also with measurement of animal productivity. The experiments reported are tedious to execute and offer much scope for arriving at erroneous conclusions. For example, incomplete collection of straw refusals would exaggerate treatment response, as unrecorded refusals would be deemed eaten. Grazing research techniques (e.g. Mayes et al, 1986) might have application for measuring quantity and quality of straw consumed.

The extent to which selective feeding by small ruminants occurs with straws other than barley needs researching. Smith et al (in press), in Zimbabwe, recently found that unsupplemented, coarse-milled (14 mm screen) maize stover offered to lambs of 37 kg liveweight, at 15, 20, 25 or 30 g kg^{-1} W d^{-1}, resulted in intakes of 23.2, 21.4, 22.3 and 29.1 g DM kg^{-1} $W^{0.73}$ d^{-1}. These rates were associated with refusal rates of 42, 61, 67 and 64%. When supplemented with protein (270 g DM per lamb, daily), maize stover intakes were improved; 26.6, 29.4, 25.3 and 36.1 g DM kg^{-1} $W^{0.73}$. The authors found little difference between the chemical composition of the stover offered and refused, but admitted to difficulties in collecting representative samples. Clearly more work is required. The same study involved feeding unsupplemented rotor-slashed maize stover to steers at 15, 20, 25 or 30 g DM kg^{-1} W d^{-1}. Intakes increased with increasing rates of offer; 41.5, 42.9, 49.9 and 49.0 g DM kg^{-1} $W^{0.73}$. These intakes were associated with refusal rates of 31.8, 48.5, 51.2 and 59.5%. The authors were unable to conclude whether or not the greater intakes by steers were due to selective feeding.

The work of Capper et al (1986), Tuah et al (1986), Ramazin et al (1986), Givens (1987) and Doyle et al (1986b) stresses the magnitude of the differences in feeding value between straws of a given type. Differences in leaf:stem ratio probably account for much of this. Other factors, such as content of soluble phenolics (Reed, 1986) may further contribute to differences in nutritive value between tropical crop residues. Interactions between straw allowance rate and straw type, as affecting selectivity and intake, are therefore likely. Zemmelink (1986) has clearly shown this to be so for tropical forages.

The need to chop residues requires clarification. As indicated earlier, studies on feeding straws/stovers invariably use chopped material to facilitate handling and minimise selection. Experiment 3 showed no clear differences due to physical form, although intake of long straw tended to be greater than that of chopped straw. A recent experiment at Reading with goats allowed refusal rates of 25% showed that intake of barley straw treated with sodium hydroxide using a dip method (straw in long form) was markedly higher than that of straw treated using a commercial on-farm method (JF machine - straw shredded) (Wrathall et al, in press). Goats appeared to find shredded straw unpalatable. The case for chopping will vary with type of crop residue. This subject needs more research.

The selective feeding associated with generous feeding of straw, shown by the Reading experiments, is likely to have implications concerning the need for nitrogen supplementation of crop residues. The extent to which interactions occur between crop-residue feeding rates and supplementation needs examining. Type of supplement could also have influence. The homogeneous nature of milled and pelleted concentrates precludes selective feeding but this would not be the case with sun-dried forage legumes. Physical form of the latter therefore needs consideration, along with the extent to which selective feeding is affected by the type of crop residue.

A feeding strategy allowing goats and sheep to reject 50% of the straw offered would be clearly wasteful and could only be justified if the rejected straw could also be used. Experiment 6 demonstrated that rejected straw can be refed and high levels of digestible straw intake achieved if it is treated with ammonia. Feeding untreated straw to allow 50% refusals and refeeding these after ammonia treatment would result in little wastage and high intakes of digestible straw. The economics of such a strategy need investigating as labour costs would be high. A simpler approach would be first to graze the straw in the field and then collect the residues after grazing and refeed it either after upgrading or with generous supplementation. Another strategy would be to feed straw generously to goats and then offer the refusals to less-selective ruminants, such as cattle or buffalo. In future such refusals might well have value for industrial purposes (Hartley et al, 1987) also, especially in developing countries (e.g. paper products, hardboards, egg-trays etc).

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DISCUSSION

Thomson: Would it be feasible to upgrade the stem fraction rather than treat the whole crop?

Aboud: Treating only the stem would reduce the amount of material to be processed, thereby reducing costs of feeding.

Ørskov: Your results suggest that goats eat more than sheep but the opposite may occur with different groups of animals. The extent to which sheep and goats select leaf material depends upon local conditions. I have found that sheep will select leaf blade material in barley straw but cannot separate leaf sheath from the stem. Since, in the United Kingdom, leaf blade may constitute only 15% of the weight of the straw, selection may be less important.

Aboud: We found it difficult to fractionate the refusals. My statement regarding the superiority of goats was qualified as relating to our conditions but is in agreement with the bulk of the scientific literature. So far we have no data on the relative amounts of leaf blade and sheath selected.

Van Soest: Selectivity of feeding is less important in temperate regions than in the tropics because there is less difference in feeding value among plant parts under temperate conditions. In the tropics selection may be vital since the overall value of the feeds available are often sub-maintenance.

Pearce: In Australia we have found that sheep will remove leaf sheath from stems but the response is highly variable. Some animals will exhibit no selection at all whilst others will effectively remove sheath material.

Thomson: The choice of a refusal level in feeding experiments is difficult. At ICARDA we use a level of 20% but follow local farmers' practice of fine chopping.

Little: Experiments have been conducted relating intake of legumes and grasses to the level of refusals allowed. These experiments indicate that a 20% refusal level is the minimum amount that should be allowed. In Cameroon, on-station experiments have shown that sheep perform better than goats, but in the villages goats out-perform sheep.

SESSION 2

FACTORS LIMITING THE NUTRITIVE VALUE OF CROP RESIDUES

General discussion

Thomson: At ICARDA a large number of parameters have been used to select barley varieties with improved straw quality. If such parameters as polyphenolics are added to the selection criteria there is a danger of making the task of plant breeders too complicated.

Capper: One approach could be to use appropriate parameters to calibrate a near-infrared-reflectance spectrophotometer, which could subsequently be used to screen a larger number of samples.

McAllan: Near-infrared-reflectance spectrophotometry has been used at an early stage in the breeding and selection of high-lysine barley, but effective calibration requires analysis of 30 to 50 samples. Nuclear magnetic resonance is an alternative promising technique.

Onim: I believe it would not be worthwhile to start selecting for straw quality at an early stage in the breeding process. It would be more productive to work with released varieties or to study the straw quality of promising material. The primary objective should be to increase grain yields. Selection for straw quality may detract from the primary focus of increasing grain yield.

Jenkins: If the plant breeder is presented with a large number of characteristics to select for there is less likelihood of producing a variety at the end of the day. It may be possible to select for a single important factor if the animal nutritionists can identify a reliable indicator of feeding value.

Reed: We hope to present data in the following sessions of the workshop which will show the possibility of identifying crop residues with superior quality. However I agree that routine screening may be impracticable and work may be most appropriate towards the end of the breeding process. The first step is to examine each species and identify factors limiting nutritive value.

Schildkamp: The conflict between straw and grain may be less apparent at the farm level. If straw has a lower nutritive value the farmer will have to feed other materials to his animals. In the Ethiopian highlands there is a trend towards growing forage which, by taking up land that could be devoted to cereals, reduces grain production.

Said: A compromise might be for the plant breeder to produce two types of varieties. Varieties that respond to a high level of inputs could be introduced for farmers interested in grain production; for the farmer interested in both straw and grain, dual-purpose varieties might be bred. However I also support the view that evaluating gene banks may not be productive.

Gupta: I believe it may be necessary to go back to gene banks, but this will depend upon particular circumstances. Where food is in short supply the first priority must be for food grains, but where there is a surplus of food grain but a shortage of feed for livestock more emphasis should be placed on crop residues.

Khush: Higher grain yields need not necessarily be achieved at the cost of lower crop residue value. Since farmers apply more nitrogen fertiliser to higher yielding varieties this may increase the nitrogen content of the residues. In other circumstances, where there is a grain surplus this might be used to supplement the crop residues.

Ørskov: I have screened over 100 varieties of different crops and found no correlation between grain yield and straw quality.

Thomson: It is clear that nutritionists still have a lot to do to identify factors affecting the nutritive value of crop residues but there is clearly a strong desire to work with plant breeders.

SESSION 3

THE EFFECT OF GENOTYPE AND ENVIRONMENT ON THE NUTRITIVE VALUE OF CROP RESIDUES

CONSISTENCY OF DIFFERENCES IN NUTRITIVE VALUE OF STRAW FROM DIFFERENT VARIETIES IN DIFFERENT SEASONS

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INTRODUCTION

The recognition that straws from different cereal varieties vary considerably in nutritive value is relatively recent (Pearce et al, 1979; Kernan et al, 1984; Bainton et al, 1987; Tuah et al, 1986), although straws have been fed to ruminants for millenia. While farmers have observed differences between types of cereal straw, e.g. wheat and barley, there has been no clear recognition of the extent to which varieties differed. There is no doubt that this late recognition of very important differences is a result of analyses which were inadequate to describe differences, e.g. gross chemical analysis. Assessment of varieties by *in vivo* digestibility trials was too cumbersome. In recent years biological methods, such as *in vitro* digestion in rumen fluid or incubation of the substrate in nylon bags in the rumen, have revealed large differences in nutritive value in the absence of large differences in gross chemical composition (Ramazin et al, 1986).

A further improvement in biological methods to estimate nutritive value is reported by Ørskov et al (in press). They observed that by describing substrate disappearance from nylon bags over time, i.e. by withdrawing nylon bags at different time intervals, it was possible to assist also in predicting voluntary intake because both the disappearance rate and extent of digestion could be described using the exponential equation developed by Ørskov and McDonald (1979). The formula $p=a+b(1-e^{-ct})$, where p is degradation at time (t), has been extensively used. With 10 straws varying widely in degradation characteristics it was possible, using a multiple correlation of a, b and c, to predict intake and growth rate very accurately and account for 90% or more in variability (Ørskov et al, in press). It can be seen that (a+b) is an expression of the potential extent of digestion while c is the rate constant of the disappearance of the insoluble but fermentable fraction (b).

EFFECT OF STRAW VARIETY ON ANIMAL PERFORMANCE

It is a valid question to ask whether the effects of differences among varieties are large enough to be reflected significantly in animal performance. An example is given in Table 1. Three straws were fed to steers and their intake and growth rate recorded. Although there were only small differences in the extent (a+b) of digestion of Golden Promise and Corgi, the rate constant for Corgi was about 60% greater than that of Golden Promise. As a result the steers ate more and grew better on Corgi straw than on Golden Promise straw. Gerbel straw was inferior to the other varieties for both extent of digestion and rate constant. The data taken from Ørskov et al (in press) reflect that nutritive value cannot adequately be described by a single static measurement but that a combination of the rate constant and potential extent of digestion can account for most of the variability in intake of straws.

Table 1. Effect of barley variety on straw intake and performance by cattle and degradation characteristics of the straw.

Variety	Extent (a+b)	Degradation rate constant hr^{-1}	Growth rate (g d^{-1})	Intake (kg DM d^{-1})
Gerbel	38.9	0.0337	106	3.43
Golden Promise	55.5	0.0303	198	4.43
Corgi	52.1	0.0483	400	5.16

CAUSES OF DIFFERENCES AMONG VARIETIES

The different morphological fractions, i.e. leaves and stems, vary considerably in nutritive value, particularly in temperate cereals such as wheat, oats, barley and rye in which the leaf and leaf sheath portion may be up to twice as digestible as stems. This is not so with rice straws (Walli et al, in press; Bainton et al, 1987), in which the leaves are generally slightly less digestible than stems. Some average values of morphological proportions are given in Table 2. It is clear that differences in the amount of leaf that adheres to the straw at harvesting can substantially change the nutritive value and some of the difference between varieties can be explained by differences in the leaf:stem ratio. However, Ramazin et al (1986) found that leaf-to-stem ratio only accounted for about 20% of the difference in nutritive value between two varieties. The largest differences were due to differences in degradability of both stems and leaves. They also

Table 2. Average morphological fractions of various cereal straws.

Fraction	Percentage of fraction in			
	Rice	Wheat	Oats	Barley
Leaf + sheath	65.6	33.9	31.0	45.1
Internodes	20.2	46.5	56.9	44.6
Chaff	6.2	13.8	4.6	4.5
Nodes	8.0	5.7	7.3	5.7

showed that stems from straw benefit much more from chemical treatment than leaves, implying that stemmy varieties benefit most from chemical treatment.

DIFFERENCES BETWEEN YEARS AND VARIETY x YEAR INTERACTION

It is obviously of interest to plant breeders to know whether the ranking of straws according to quality is consistent between years and also, to some extent, whether there is a large between-year variation.

During the past 3 years the nutritive value of straw from several varieties of winter barley, spring barley, wheat and oats has been studied at the Rowett. In both wheat (Table 3) and spring barley (Table 4) there were significant differences among varieties and among years ($P<0.001$). The variety x year interaction was more significant in spring barley ($P<0.01$) than in wheat ($P<0.05$). However, ranking was generally similar

Table 3. Differences in degradability of winter wheat straw among varieties and years.

Variety	48-hour degradability (%)		
	Year 1	Year 2	Year 3
Aquila	35.0	42.4	45.2
Avalon	36.9	47.7	48.3
Boxer	37.0	38.9	50.5
Brigand	38.7	41.9	54.9
Brimstone	37.6	45.4	54.9
Brock	37.8	46.4	56.4
Galahad	37.7	46.1	55.2
Longbow	38.4	43.5	52.0
Norman	36.4	44.7	51.9
Renard	37.0	42.1	47.8

Significance of difference:	
Between varieties	$P<0.001$
Between years	$P<0.001$
Variety x year interaction	$P<0.05$

among years. Two years' results from oats show a great variation between years but only small differences between the six varieties tested so far (Table 5).

In winter barley there were highly significant differences between the varieties and between years but the variety x year interaction was not significant (Table 6). In comparison with Table 4 for spring barley it can be seen that the nutritive value of winter barley straw is consistently lower than that of spring barley straws.

Table 4. Differences in degradability of spring barley straw among varieties and years.

Variety	48-hour degradability (%)		
	Year 1	Year 2	Year 3
Celt	46.4	39.6	45.5
Corgi	58.9	46.2	52.7
Doublet	61.1	45.9	57.9
Golden Promise	40.3	34.4	41.5
Golf	46.9	37.7	42.6
Heriot	54.4	42.1	50.6
Klaxon	48.8	34.3	39.9

Significance of difference:

Between varieties	P<0.001
Between years	P<0.001
Variety x year interaction	P<0.01

Table 5. Differences in degradability of oat straw among varieties and years.

Variety	48-hour degradability (%)	
	Year 1	Year 2
Ballard	51.5	36.7
Cabana	51.1	38.7
Dula	46.5	38.3
Leanda	47.6	36.7
Matra	48.3	40.7
Trafalgar	46.7	37.6

Table 6. Differences in degradability of winter barley straw among varieties and years.

Variety	48-hour degradability (%) Year 1	Year 2
Gerbel	32.7	43.4
Halcyon	34.3	43.5
Igri	35.6	44.4
Kaskade	38.8	48.6
Magie	41.0	49.5
Marinka	37.5	44.6
Maris Otter	32.9	48.1
Nevada	36.3	47.9
Opera	40.4	44.8
Panda	37.7	46.9
Ripkin	42.5	50.2
Pirate	37.1	46.1

Significance of difference:	
Between varieties	P<0.001
Between years	P<0.001
Variety x year interaction	NS

CAUSES OF YEAR-TO-YEAR VARIABILITY AND VARIETY x YEAR INTERACTION

Some of the variation between years can be accounted for by differences in the content of soluble nutrients. For instance the mean values for the 48-hour degradability of the wheat varieties were 37.2, 43.9 and 51.7% in year 1, 2 and 3, respectively. The respective content of soluble nutrients for the 3 years were 3.4, 11.4 and 16.1%. Thus it appears that most of the variability could be accounted for in this instance by differences in the content of water-soluble nutrients. For the spring barley straws in 1985 and 1986 the solubility cannot account for a large proportion of the differences except perhaps to make the ranking more consistent. In Table 7 the spring barley straws have been given where the water soluble component was subtracted. It is clear that the ranking here was very consistent for the 2 years.

Table 7. Effect of year on ranking order of spring barley varieties using the potential degradability less the water-soluble material.

1985		1986	
Variety	Potential (%)	Variety	Potential (%)
Doublet	39.9	Doublet	51.1
Corgi	37.1	Corgi	45.3
Heriot	36.7	Heriot	44.3
Golf	34.4	Celt	37.5
Celt	33.8	Golden Promise	37.0
Golden Promise	30.2	Golf	36.8
Klaxson	26.8	Klaxson	32.1

Based on the results presented it is evident that there is a component of variety x year interactions the causes of which are not clear and which need further investigation. It is possible that variation in soluble materials or leaf-to-stem ratio could be responsible for this. It is abundantly clear however, that varieties vary and on the whole the ranking is such that it can with confidence be selected for. In the work carried out with more than 100 varieties a significant correlation between grain yield and straw quality has never been noted, nor has there been any significant relationship between N content and nutritive value. Thus it should be possible to select for improved nutritive value of straw without reducing grain yield. Whether environmental stresses such as drought will produce interactions with variety is not known with certainty but resources should be directed to solve these problems rapidly so that plant breeders can with confidence select for straw quality as well as grain yield and quality.

METHODS OF ROUTINE ANALYSIS

Although gross chemical analysis cannot adequately predict nutritive value, several biological measurements can (Table 8). The most promising purely laboratory method is cellulase digestion of the material after neutral-detergent extraction. However, it is difficult to standardise the mixtures of enzymes present in commercial preparations. Both *in vitro* measurement using rumen fluid and nylon-bag incubation can be used to provide reliable information for plant breeders on ranking of nutritive value.

CONCLUSION

While variety x year interaction exists, the ranking order is altered only little. The differences among varieties need to be exploited by plant breeders, particularly in areas where straw

Table 8. Correlation between chemical and biological parameters of straw and intake and digestibility by steers.

Measurement	Dry-matter intake	Growth rate
Crude fibre	-0.70	-0.57
Neutral-detergent fibre	-0.79	-0.77
Acid-detergent fibre	-0.86	-0.79
Lignin	-0.75	-0.72
Cellulase digestion of neutral-detergent fraction	0.88	0.95
Near-infrared (calibrated to *in vitro* measurement)	0.86	0.87
In vivo digestibility at maintenance in sheep	0.70	0.77
In vitro digestibility	0.86	0.90
Multiple correlations of a, b and c from exponential equation using nylon bags	0.89	0.96

is a very large component of feeds for ruminants. The possibility of increasing digestibility of straws or stovers by 10 to 20% can have immense implications for animal production by small farmers in many regions of the world.

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DISCUSSION

Van Soest: Firstly, I want to correct a criticism made of the neutral-detergent system. We do not use cellulases; all our rates are done using a modified Tilley and Terry *in vitro* technique where the second stage is replaced by extraction with neutral detergent.

Secondly, your rate constants and extents look low relative to our values. My worry is that nylon bags are very prone to microbial contamination, which leads to an underestimate of the real degradation.

Ørskov: The degradability of our straw is actually very high, usually between 40 and 60%.

Van Soest: We find in the average wheat straw that true digestibility is in the order of 60 to 65% when the apparent digestibility is in the forties, the difference being metabolic and microbial matter. The question arises, how did you wash your bags and wash the microbial contamination out?

Ørskov: We washed the bags in a washing machine by a rinsing process.

Van Soest: That is probably inadequate to remove the attached bacteria.

Ørskov: It may well be but if we could find a better method to predict intake and growth rate I would adopt it. If we can get correlations of 0.96 using the extent and rate constant that is really not too bad. If there was a laboratory method that would do it better I would adopt it.

Van Soest: I have to make the criticism of the rate constants. You have values as low as 2%, which we have never seen. Microbial attachment reaches a maximum at 12 to 18 hours, when contamination is greatest. Then you get lysis and cannibalism by micro-organisms and contamination declines. Contamination at times at the top of your logarithmic curves will bias your slopes and cause error.

Ørskov: I do not think we have shown rate constants as low as 2%. The rate constants are between 3 and 5% per hour, which is what one would expect for these sorts of materials. We have only found rates as low as 2% in stems.

Thomson: Did these straws come from a field station or farmers' fields.

Øskov: The varieties we used in feeding trials were taken from big fields. The other materials were from small-plot variety trials.

Thomson: Are you surprised that the nodes have such a high degradability?

Øskov: Yes I am. I thought they were going to be the lowest, but they are always higher than stems.

Pearce: You stated that poor-quality straws always respond better to chemical treatment than high-quality straws. Is that because low-quality straws have a higher proportion of cell wall?

Øskov: No, it's probably due to a higher stem content. One has to be careful of generalising, but on the whole the stems respond much better than leaf.

Pearce: If you have a higher proportion of stem you certainly have a higher proportion of cell wall, and chemicals react with cell walls rather than cell contents.

Schildkamp: You mentioned that it was difficult to make recommendations to breeders. In wheat straw you showed that leaves are more digestible than stems. Would you not make the recommendation to select for leafiness?

Øskov: I would definitely recommend selection for leafiness, but it is not sufficient, because leaves also vary in value. If I were asked to recommend a technique for ranking varieties for nutritive value, I would recommend a relatively short incubation period, because you are not after a number that means something to animal nutritionists. If you use a short incubation period of maybe 24 hours you will get an idea of the trajectory of the curve, both the rate and extent.

GENETIC VARIATION IN THE FEEDING VALUE OF BARLEY AND WHEAT STRAW

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INTRODUCTION

Straw is one of the most important feeds for sheep in West Asia. Barley and wheat straw may constitute half the dry matter of the diets of pregnant and lactating ewes in winter and stubbles make an important contribution to the maintenance of sheep flocks in the summer. In Syria, farmers have rejected an improved barley variety because its straw was less palatable to sheep than straw from a barley landrace (Nygaard, 1983). Voluntary intake and digestibility studies have confirmed farmers' observations that feeding value of straws differs among varieties (Capper et al, 1986).

It has been suggested that the proportions of leaf and stem in the straw, together with variations in chemical composition and microstructure of morphological fractions, are responsible for genetic variation in the feeding value of straw (Capper, in press). Environment also appears to affect straw quality, such that material from higher rainfall locations contains less leaf than that from semi-arid locations.

This paper reports observations on the morphological composition and *in vitro* digestibility of straw and examines the possibility of relating straw quality to varietal characteristics such as plant height, time to grain maturity and grain yield. The effects of environment on straw quality and the size of variety x environment interactions are considered. Data are presented on the use of the nylon bag technique for predicting the digestible dry matter intake of straw from different barley varieties and comparisons are made with the use of chemical composition and varietal characteristics for predictive purposes. Since ewe feeding in winter utilises a major part of the available feed resources in Syria, experiments are described on the effects of variety on straw consumption and milk yields in Awassi ewes.

MATERIALS AND METHODS

In 1985 samples of barley and wheat were taken from breeding and variety trials at Tel Hadya, Breda and Bouider, situated between 25 and 100 km south of Aleppo in northwest Syria. Plant height, days to maturity or heading and grain yield were measured on individual plots. There were two replicates for F_3 bulk selections of barley, three for barley landraces and four for wheat variety trials. Mid-plot samples, which weighed approximately 100 g, were separated into heads, leaf blade, leaf sheath and stem fractions. Samples of barley landraces and F_4 bulk selections, harvested from trials with three replications in 1986, were separated into heads and straw. *In vitro* digestibility analysis (Tilley and Terry, 1963), standardised using samples of straw of known *in vivo* digestibility, was carried out on leaf blade, leaf sheath and stem fractions collected in 1985 and on straw harvested in 1986.

Material for feeding trials using unsupplemented barley straw was grown at Tel Hadya (35° 55′ N, 36°55′ E) using a seed rate of 100 kg ha^{-1} and fertilizer levels of 50 kg N ha^{-1} and 50 kg P_2O_5 ha^{-1}. Rainfall was 229 mm in 1984 and 373 mm in 1985. Prior to harvest, plant height and days to maturity were recorded. Quadrats were cut to estimate grain and straw yields and samples of the crop were fractionated to determine the proportion of leaf. In 1984 the crops were harvested by machine at a cutting height of 20 cm but in 1985 the crops were hand-pulled. Material from each variety was passed through a stationary thresher to give chopped straw with a stem length of 2.5 cm. Digestible dry matter intake was measured with Awassi wethers in digestibility crates. Four measurements were made on each straw. A refusal level of 20% was used. Trials lasted 28 days with voluntary intake being measured and faeces collected over the final 14 days. The crude protein (MAFF, 1981), modified acid-detergent fibre (MAFF, 1973) and neutral-detergent fibre (Goering and Van Soest, 1970) contents of the straws were determined prior to feeding. Nylon bag degradability techniques (Ørskov et al, 1980) were applied to straws evaluated in feeding trials using wethers.

Straw for feeding trials with ewes was obtained from crops grown at Tel Hadya in 1986 using similar methods to those described above. During weeks 2 to 6 of lactation, 36 individually penned ewes were randomly allocated to four straws from different varieties. Straw intake was recorded using a refusal level of 20%. A fixed level of concentrate was provided. The concentrate contained 78% barley grain, 10% cottonseed meal, 10% wheat bran, 1% salt and 1% dicalcium phosphate. Animals were weighed weekly. Milk yields were determined by hand milking and by subsequently weighing lambs before and after suckling. During weeks 8 to 12 of lactation ewes on straw from each variety were allocated to three subtreatments with different levels of concentrate feeding according to previous levels of straw consumption. Straw intake, liveweight changes and milk yields were recorded as described above.

RESULTS

Morphological composition of straws

The mean morphological composition of straw of barley and wheat varieties grown at ICARDA is given in Table 1. Leaf blade and sheath made up a higher proportion of the mature plant than stem.

Table 1. **Proportions of morphological fractions in barley and wheat straw harvested in 1985 (mean ± SE).**

Crop	Number of varieties	Leaf blade		Leaf sheath		Stem	
		Mean	SE	Mean	SE	Mean	SE
Barley F_3 bulk	38	0.42	0.02	0.24	0.01	0.34	0.01
Barley landraces	20	0.39	0.02	0.24	0.01	0.37	0.01
Wheat (regional trial)	24	0.29	0.01	0.24	0.01	0.48	0.01
Wheat (elite trial)	29	0.37	0.01	0.26	0.01	0.38	0.01

Correlation coefficients (r) given in Table 2 show that the proportion of leaf blade was determined by plant height, straw from taller varieties of barley and wheat containing less leaf blade than that of shorter varieties. In the F_3 barleys, the higher yielding varieties had significantly less leaf blade in the straw. In barley landraces and the wheat trials, days to maturity or heading were associated with an increase in the proportion of leaf blade and a reduction in the proportion of stem. These effects were not statistically significant because of the dominant influence of plant height in determining proportion of leaf blade in the straw.

Table 2. **Relationships (r) between barley and wheat characteristics and proportions of morphological fractions in straw harvested in 1985.**

Crop	Characteristic	Leaf blade	Leaf sheath	Stem
Barley F_3 bulk (n=38)	Plant height	-0.75***	0.25	0.74***
	Days to maturity	-0.26	0.09	0.27
	Grain yield	-0.65***	0.14	0.69***
Barley land-races (n=20)	Plant height	-0.58**	0.11	0.60**
	Days to maturity	0.13	0.17	-0.18
	Grain yield	-0.15	-0.05	0.20
Wheat (regional trial) (n=24)	Plant height	-0.29	0.40	0.21
	Days to maturity	0.21	0.37	-0.31
	Grain yield	0.19	0.24	-0.24
Wheat (elite trial) (n=29)	Plant height	-0.78***	0.19	0.76***
	Days to maturity	0.21	-0.08	-0.20

=P<0.01;*=P<0.001.

In vitro digestibility of morphological fractions

In barley varieties, leaf blade was more digestible than leaf sheath which was, in turn, more digestible than stem (Table 3). In wheat, leaf blade was more digestible than stem. Digestibility of leaf sheath was similar to that of leaf blade in one wheat trial but was similar to stem digestibility in another wheat trial. The effects of varietal characteristics on the digestibility of the different fractions were, generally, non-significant and variable (Table 4). In barley landraces stem digestibility was lower in taller varieties. Higher grain yields tended to be associated with lower digestibility of the fractions. In some cases a positive relationship was observed but, with one exception, these were not statistically significant.

Table 3. *In vitro* digestibility (%) of morphological fractions of barley and wheat straw harvested in 1985.

Crop	Number of varieties	Leaf blade		Leaf sheath		Stem	
		Mean	SE	Mean	SE	Mean	SE
Barley F_3 bulk	38	55.5	0.6	45.4	0.6	39.4	0.5
Barley landraces	20	48.1	0.8	42.4	0.7	36.6	0.9
Wheat	24	39.0	0.4	38.7	0.2	30.6	0.2
Wheat	50	42.2	0.2	30.5	0.3	29.6	0.2

In vitro digestibility of straw from different locations

Data presented in Table 5 show that the digestibility of straw from a given variety can be affected very considerably by environment. Barley straw from Tel Hadya was less digestible than that from the drier sites, Breda and Bouider. Table 6 summarises analyses of variance associated with the data in Table 5. Most of the variation in straw digestibility was associated with location,

Table 4. **Relationships (r) between barley and wheat characteristics and *in vitro* digestibility of morphological fractions in straw harvested in 1985.**

Crop	Characteristic	Leaf blade	Leaf sheath	Stem
Barley F_3 bulk (n=38)	Plant height	-0.34*	-0.26	-0.25
	Days to maturity	0.01	-0.03	-0.08
	Grain yield	-0.11	-0.12	-0.33*
Barley land-races (n=20)	Plant height	0.14	0.14	-0.45*
	Days to maturity	0.09	0.12	0.18
	Grain yield	-0.06	0.10	-0.36
Wheat (n=24)	Plant height	-0.14	0.20	0.28
	Days to maturity	-0.02	-0.11	0.09
	Grain yield	-0.08	-0.37	-0.13
Wheat (n=50)	Plant height	0.02	0.04	-0.19
	Days to maturity	0.06	0.01	0.16
	Grain yield	0.09	-0.20	-0.01

*=P<0.05.

Table 5. *In vitro* straw digestibility for barley varieties harvested at three locations in 1986.

	Site (average rainfall, mm)					
	Tel Hadya (330)		Breda (283)		Bouider (205)	
Trial	Mean	SE	Mean	SE	Mean	SE
Landraces, Arabic Aswad type	37.2	0.26	43.3	0.25	52.9	0.37
Landraces, Arabic Abiad type	40.8	0.23	46.5	0.28	51.7	0.44
F_4 bulk selections	36.7	0.29	45.9	0.33	55.3	0.32

but variety had a greater effect than the interaction between location and variety. In the case of landraces of the black, or Arabic Aswad, type the effects of variety were significant.

Table 6. Summary of analyses of variance for location, variety and interaction effects on the *in vitro* digestibility of barley straw harvested in 1986.

Trial	Number of entries	Location	Variety	Interaction
Landraces, Arabic Aswad type	25	4603.8***	11.5***	4.2
Landraces, Arabic Abiad type	20	1797.8***	6.8	6.3
F_4 bulk selections	25	4331.4***	7.6	3.8

***=P<0.001.

Feeding trials with unsupplemented barley straw

The digestible dry matter intake (DDMI) of straw by Awassi sheep was affected by barley variety (Table 7). However, the ranking of straws for

Table 7. Digestible dry matter intake (g kg^{-1} $W^{0.75}$ day^{-1}) of straw from seven barley varieties grown in successive seasons.

Variety	Year of harvest 1984	1985
C-63	21.89 (1)	21.41 (4)
Antares	18.35 (2)	27.31 (1)
Rihane	18.26 (3)	21.48 (3)
Badia	17.70 (4)	16.42 (7)
ER/Apam	16.73 (5)	16.59 (6)
Beecher	16.57 (6)	16.98 (5)
Arar	15.49 (7)	22.09 (2)

Straw harvested by machine in 1984 and by hand in 1985.
Numbers in parentheses are ranks.

DDMI varied between 1984 and 1985. The variety Arar, for example, had the lowest DDMI in 1984 and the second highest DDMI in 1985. In 1985 DDMI was closely and positively associated with dry-matter digestibility and nylon-bag degradability (NBD) of the straw but DDMI was not associated with these parameters in 1984 (Table 8). Crude-protein content was positively associated with DDMI and acid-detergent fibre content was negatively

Table 8. Prediction (r) of digestible dry matter intake (g kg^{-1} $W^{0.75}$ day^{-1}) of straw from various characteristics of seven barley varieties grown in successive seasons.

Characteristic	Year of harvest 1984	1985
Digestibility (%)		
In vivo dry matter	-0.12	0.97***
Nylon-bag degradability (%)		
48-hour dry matter	-0.30	0.76*
72-hour dry matter	n.d.	0.84*
Chemical composition (%)		
Crude protein	0.90**	0.94**
Acid-detergent fibre	-0.40	-0.83*
Neutral-detergent fibre	0.24	-0.54
Varietal characteristics		
Leaf proportion	0.58	0.64
Days to maturity	0.61	0.81*
Stem height (cm)	0.20	-0.26
Grain yield (kg ha^{-1})	-0.27	-0.51
Straw yield (kg ha^{-1})	0.67	0.01

*=P<0.05; **=P<0.01; ***=P<0.001; n.d.= not determined.

associated with DDMI. Leaf proportion and days from planting to maturity were positively associated with straw feeding value but stem height did not influence DDMI. Increase in DDMI was associated with a reduction in grain yield but the relationships were non-significant. The regression coefficients for these relationships (Table 9) suggest that for each 1.0 g kg^{-1} $W^{0.75}$ day^{-1} increase in DDMI, grain yields will be reduced by around 70 kg ha^{-1}.

Table 9. Relationships between grain yields (kg ha^{-1}) and intake of digestible dry matter (g kg^{-1} $W^{0.75}$ day^{-1}) of barley straw.

Year of harvest	Regression coefficient	Intercept
1984	-62.3	3141.3
1985	-80.1	3401.2

Feeding trials with Awassi ewes

During weeks 2 to 6 of lactation ewes consumed more straw from the 2-rowed varieties Arabic Abiad and ER/Apam than from the 6-rowed varieties Beecher and C-63 (Table 10). The animals performed best when fed straw from the local landrace Arabic Abiad. Animals fed Beecher straw lost most liveweight and those fed straw from C-63 had low daily milk yields. In weeks 8 to 12 of lactation, during which each straw was fed with three levels of concentrate, milk production was highest on Arabic Abiad straw and lowest on straw

Table 10. Concentrate consumption, voluntary intake of straw from contrasting barley varieties, liveweight changes and milk yields of Awassi ewes in weeks 2 to 6 of lactation.

Barley variety	Concentrate consumption[1]	Straw intake[1]	Live-weight change[2]	Milk yield[2]
Arabic Abiad	45.1	44.9	-39.7	1634.7
ER/Apam	45.6	44.3	-50.3	1583.6
Beecher	43.1	37.2	-95.2	1580.5
C-63	42.6	36.2	-52.9	1263.9
Mean	44.1	40.6	-59.5	1515.7
SE +	1.7	2.3	24.1	109.4

1. $g\ kg^{-1}\ W^{0.75}\ day^{-1}$.
2. $g\ day^{-1}$.

from C-63 (Table 11). Ewes fed lower levels of concentrate consumed more straw. Ewes consumed more straw from the 2-rowed varieties Arabic Abiad and ER/Apam than from Beecher and C-63.

DISCUSSION

The proportions of leaf, leaf sheath and stem vary considerably among barley and wheat straws and this variation has been shown to be caused mainly by variations in plant height and, to a lesser extent, days to maturity or heading. Considerable variation also exists in the digestibility of

Table 11. Concentrate consumption, voluntary intake of straw from contrasting barley varieties, liveweight changes and milk yields of Awassi ewes in weeks 8 to 12 of lactation.

Barley variety	Concentrate consumption[1]	Straw intake[1]	Live-weight change[2]	Milk yield[2]
Arabic	48.1	40.9	12.4	549.0
Abiad	34.6	50.2	1.9	463.3
	18.3	51.2	0.9	387.3
ER/Apam	47.4	36.9	4.3	478.3
	35.4	41.4	9.5	489.0
	19.9	49.5	3.6	307.3
Beecher	48.2	34.4	3.6	535.5
	34.4	38.0	6.7	387.7
	17.4	43.1	-5.0	355.8
C-63	43.2	31.5	6.4	314.5
	31.8	42.8	2.1	281.5
	14.2	39.1	-8.0	386.8
Mean	32.2	41.2	2.6	405.8
SE	2.0	1.1	1.2	72.9

1. g kg^{-1} $W^{0.75}$ day^{-1}.
2. g day^{-1}.

fractions but it does not appear possible to relate this variation readily to varietal characteristics. Ramazin et al (1986), using the nylon bag technique, found that differences in degradability of fractions among varieties were more important than differences in morphological composition in determining barley straw quality.

However, the varieties they tested had leaf proportions of 0.44 and 0.53 whereas leaf proportions reported in Syria for barley ranged from 0.50 to 0.81 and from 0.45 to 0.74 for wheat. This suggests that the proportion of leaf in the straw is an important factor in determining variation in straw quality. Whereas Ramazin et al (1986) suggested that only 20% of variation in straw quality can be attributed to variation in morphological composition, the results reported here on DDMI of barley straws suggest that about 40% of the variation in straw feeding value relates to variation in morphological composition. The causes of the remaining variation in straw value are not readily apparent but may relate to the chemical composition and microstructure of morphological fractions. The only relationship found between a varietal characteristic and the digestibility of a morphological fraction is that between plant height and stem digestibility in barley.

Feeding trials with lactating ewes support the contention that straw from shorter, 2-rowed varieties have higher feeding value than straw from taller, 6-rowed varieties (Capper et al, 1986). The 2-rowed varieties usually have a larger proportion of leaf in the straw than 6-rowed varieties. However, trials with unsupplemented barley straws fed to Awassi wethers suggest that there is a positive relationship between days to maturity and DDMI of straw. The results suggest overall that shorter or later-maturing varieties are likely to have better quality straw than tall or early-maturing varieties. Crude-protein content was found to be closely related to straw DDMI but this may be a consequence of higher crude protein levels in leaf material. Where animals receive protein supplements there may be no direct relationship between straw crude protein content and feeding value. The significant relationship between nylon bag degradability and DDMI in straw harvested in 1985 suggests that the technique may be of value in routine screening of straws for feeding value.

The relationship between straw feeding value and grain yield, although not significant, is of considerable importance to the farmer in deciding which variety to plant. Feeding trials with unsupplemented barley straw suggested that for each 1.0 g kg^{-1} $W^{0.75}$ day^{-1} increase in straw feeding value (DDMI), grain yields would be reduced by about 70 kg ha^{-1}. In order to increase straw feeding by about 50%, from 15 g kg^{-1} $W^{0.75}$ day^{-1} to 22.5 g kg^{-1} $W^{0.75}$ day^{-1}, grain yields would be reduced from 2200 kg ha^{-1} to about 1700 kg ha^{-1}. In semi-arid areas, where harvest indices are low, the improved quality of the straw may more than offset the reduction in grain yield. Feeding trials with lactating Awassi ewes suggest that feeding lower quality straw could reduce milk production by about one third and result in lower liveweights at the end of lactation, which could affect subsequent breeding performance.

The correlation coefficients for relationships between straw feeding value and grain yield in barley were not significant, suggesting that varieties could be chosen which combine good grain yield with superior straw feeding value. The selection or breeding of varieties of barley and wheat with superior straw feeding value depends upon stability in various measures of straw quality across years or locations. It has been demonstrated that variety has a greater effect on *in vitro* digestibility of straw than the interaction between variety and location. Thus plant breeders could select varieties that will give better quality straw in a range of environments. However, *in vitro* digestibility methods, current chemical methods and the use of varietal characteristics are not infallible in ranking varieties for straw quality and alternative methods need to be investigated. At present the use of nylon bag degradability techniques appears to hold promise.

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DISCUSSION

Øskov: Is there a correlation between straw quality and grain yield?

Capper: In *in vitro* digestibility trials both in Syria and the United Kingdom you get the same result: correlation coefficients are very low, even though sometimes they are negative.

Schildkamp: I would like to comment on rice in the Philippines where, because of taste differences, farmers grow a very old variety of rice with reddish grain for home consumption and IR36 for commercial production. Farmers preferred to feed the straw of the older variety to their water buffalo. We did not look at chemical composition but farmers said that the buffalo ate more of the straw from the older variety. They preserved some IR36 straw in case they had shortages of straw from the older variety.

Capper: In response to your comment, it appears that from chemical composition and *in vitro* analysis, selection for increased grain yield in varieties such as IR36 has not changed straw quality a great deal. I am not claiming that selection for higher harvest index has improved straw quality but at least it has not changed.

Pearce: I am quite sure that there are palatability differences between straws and between varieties that we know very little about.

Capper: Much more work is needed to determine factors that lead to these differences.

SOURCES OF VARIATION IN THE NUTRITIVE VALUE OF WHEAT AND RICE STRAWS

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INTRODUCTION

The nutritive value of cereal straws can be improved in several ways. Treatment with chemicals, such as alkali, alters the characteristics of straws and renders the cell-wall constituents more susceptible to microbial attack and thus increases straw intake and digestibility. Supplementation with limiting nutrients can also improve straw utilisation. The responses to supplementation are influenced by the characteristics of the straw: response is likely to be better with a good quality straw than with a poor quality one.

Straw quality *per se* can be improved by:

- o breeding or genetic engineering;
- o modification of agronomic practices; and
- o altering harvesting, threshing and storage methods to optimise straw feeding value.

None of these will be readily adopted because grain yield and quality are primary considerations in commercial crop production. Consideration of any form of manipulation of cereal plants requires an understanding of the sources of variation and of the nature and timing of the changes occurring during growth and development of the plant that determine its characteristics at the straw stage. This paper examines these aspects in relation to wheat and rice straws.

VARIATION IN THE NUTRITIVE VALUE OF STRAWS

The nutritive value of a feed is determined by (a) the concentration of nutrients in the feed, (b) the amount eaten, (c) the proportion of the nutrients digested and (d) the efficiency with which absorbed nutrients are used. Data on all of these components are rarely available for cereal straws, and indices, such as chemical composition and digestibility values, are commonly used to assess nutritive value. Very few *in vivo* digestibility experiments have been conducted using cereal straw fed alone (without supplements) and most digestibility measurements are made *in vitro*.

Animals fed cereal straws alone invariably lose weight, indicating that the nutritive value of these materials is low. However, published data show that there is wide variation in their nutritive characteristics (Table 1). It is not known how much of this variation is due to inherent characteristics of the plant material and how much is due to differences in the proportions of morphological fractions (leaves, stems etc.) arising from different growing conditions, harvesting procedures (particularly height of cutting) and threshing and storage methods. In feeding trials, the composition of the straw actually consumed is affected by feeding practices. Descriptions of the origin and history of straw samples are usually inadequate, so it is not possible to determine the extent to which comparisons of different straws are valid.

Examinations of separate plant fractions indicate that real variation occurs within these fractions (Table 2). It is still difficult, however, to attribute variation to genotype, environmental conditions of plant growth or interactions

Table 1. Ranges in nutritive characteristics of wheat and rice straws.

Component	Wheat straw	Rice straw
Nitrogen (% DM)	0.24[1]-0.99[2]	0.38[3]-1.52[4]
Sulphur (% DM)	0.04[5]-0.19[6]	0.01[7]-0.13[6]
In vitro digestibility (%)	21[8]-58[9]	30[3]-62[10]
Voluntary intake (kg DM 100 kg^{-1} LW)	0.6[11]-1.4[12]	1.0[13]-2.7[14]

Sources:

1. Pearce et al (1979)
2. Acock et al (1978)
3. Sannasgala and Jayasuriya (1984)
4. Roxas et al (1985)
5. CSIRO (1982)
6. NRC (1970)
7. McManus and Choung (1976)
8. Braman and Abe (1977)
9. Levy et al (1977)
10. Winugroho (1981)
11. Franklin et al (1967)
12. W.J. Wales (unpublished data)
13. Vijchulata and Sanpote (1982)
14. Devendra (1983)

Table 2. Ranges in *in vitro* organic matter digestibility (IVOMD) of morphological fractions of wheat and rice straws.

	IVOMD%	
Fraction	Wheat straw	Rice straw
Stem internode	21 - 35	42 - 77
Leaf sheath	45 - 63	38 - 56
Leaf blade	58 - 77	45 - 60

Source: Winugroho (1981).

between these factors. Although differences among cultivars have often been measured (for example, Table 3), it is not possible to state confidently that any one cultivar produces better quality straw than another, let alone to quantitate the magnitude of any apparent superiority. Differences also occur among seasons, even in the same location with similar harvesting procedures. Table 4 shows the variation in *in vitro* organic matter digestibility (IVOMD) over three seasons of two rice cultivars grown at one location in the Philippines.

Table 3. Ranges in *in vitro* digestibility of straw from wheat and rice cultivars.

Type of straw	No. of cultivars	*In vitro* digestibility (%)	Country/ reference
Wheat	20	28 - 42	USA/White et al (1981)
Rice	21	44 - 62	Australia/ Winugroho (1981)

EXPERIMENTAL APPROACHES

Special experimental strategies are required to obviate the problems described above. In studies at the University of Melbourne aimed at determining the effect of plant factors on straw quality the following approaches have been developed:

1. Plants are harvested whole and dissected into stem internodes, leaf sheaths and leaf blades

Table 4. Seasonal variation in IVOMD of straw from two rice cultivars.

	IVOMD (%)		
	1981/82[1]	1983/84[2]	
Cultivar	Wet season	Wet season	Dry season
IR 36	36	53	51
IR 42	41	41	47

Sources: 1. Roxas et al (1984).
2. Roxas et al (1985).

for separate analysis. The nodes, rachis and glumes are analysed occasionally but are sometimes discarded because they represent minor proportions of the total mass of the plant.

2. The topmost stem internode, designated S1, is analysed separately from the second internode, S2, and separately from S3, S4 and so on. In the same way, the leaf sheaths are sub-grouped into LS1, LS2 etc and the leaf blades into LB1, LB2, etc.

3. Samples are taken, usually at weekly intervals, during vegetative growth, maturation and senescence. This permits critical periods of change to be identified in relation to the subsequent feeding value of the straw.

4. The mass of a chemical component in a particular fraction is calculated. When this

is plotted against time, meaningful patterns of change can be readily seen.

This overall approach reveals real changes occurring in plants in relation to ontogenetic events and permits the assessment of changes in terms of indices of nutritive value, such as *in vitro* digestibility. Obviously, in practice and in animal feeding experiments, straw is still used as harvested, but it is useful to monitor feed intake by separating samples of feed offered and refused into morphological fractions to help explain results when selection of dietary components occurs.

In assessing the nutritive value of mature, senescent and dead forages a clear distinction should be made between the cell wall, measured as neutral-detergent fibre (NDF), and the cell contents, measured as neutral-detergent solubles (NDS% = 100 - NDF%), because the cell wall is usually slowly and poorly digestible, while the cell contents may be highly and rapidly digestible. In the following discussion the characteristics of the cell wall and the cell contents are dealt with separately and it will be seen that opportunities for manipulation differ for these two components.

With wheat straws, greater emphasis is placed on the stem (internodes) fraction than the leaf (sheath and blade) fraction because the stem comprises a much larger proportion of the straw than leaves (Table 5). More leaf material is lost during harvesting and threshing than stem, and therefore the straw offered to animals contains a larger proportion of stem than indicated in Table 5. In whole rice straw, the proportions of internodes, sheaths and blades tend to be more equal but again more leaf blade material is likely to be lost during harvesting and threshing.

Table 5. Percentage of whole culm weight of wheat and rice straw in internodes, nodes, leaf sheaths and leaf blades.

	Wheat straw	Rice straw
Internodes	50	31
Nodes	8	5
Sheaths	24	36
Blades	18	28

Source: Winugroho (1981)

CELL WALL

The plant cell wall comprises cellulose, hemicellulose, pectin, lignin, minerals and protein. These, with the exception of pectin, are insoluble in neutral-detergent solution. The composition of cell walls of both wheat straw and rice straw is variable (Table 6), although the ranges in cellulose and hemicellulose levels in wheat are relatively small. In a limited number of analyses, Winugroho (1981) found that the ranges in NDF composition in stem internodes, leaf sheaths and leaf blades were usually narrower than in samples of whole straws (Table 7). Thus, much of the variation shown in Table 6 may be due to differences in the proportions of plant morphological fractions, rather than differences in cell wall composition *per se*. Insufficient data are available in the literature to show the extent to which cell wall composition varies in morphological fractions.

Table 6. Ranges in the composition of NDF (as % of NDF) in wheat and rice straws.

Component	Wheat straw	Rice straw
Cellulose	50[a]-56[b]	41[g]-57[g]
Hemicellulose	28[c]-39[d]	4[g]-39[h]
Lignin	9[b]-18[a]	8[h]-18[g]
Residual ash	1[e]- 8[f]	8[h]-38[g]

Sources: a. Koller et al (1978).
b. Yu et al (1975).
c. Pearce et al (1979).
d. Ayres et al (1976).
e. Alawa and Owen (1984).
f. Ben-Ghedalia and Miron (1981).
g. Roxas et al (1984).
h. Yoon et al (1982).

This argument may be taken further to consider possible variation in the proportion of different cell types (epidermal, mesophyll, schlerenchyma, parenchyma etc) within a morphological fraction and the extent to which variation occurs in the characteristics of the cell wall of a particular cell type. This has been studied in ryegrass (*Lolium*) leaves (Gordon et al, 1985) but not in cereal species.

Studies on the developing plant can provide important information on the types of manipulation that might be used to improve nutritive value and on the critical time periods during which a plant expresses characteristics important in determining straw quality. In the growing and maturing plant, the partitioning of mass into the different morphological fractions follows a generally well-

Table 7. Ranges in the composition of NDF (as % of NDF) in stem internodes, leaf sheaths and leaf blades of wheat and rice straws.

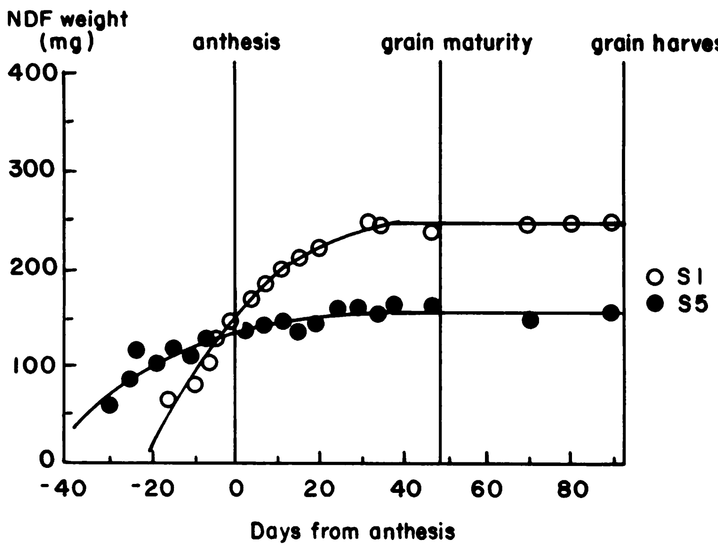
Component	Wheat straw			Rice straw		
	Internodes	Sheaths	Blades	Internodes	Sheaths	Blades
Cellulose	50-53	48-48	42-45	43-58	49-50	37-41
Hemicellulose	30-31	32-36	22-30	21-39	21-29	22-25
Lignin	15-17	8-9	8-9	11-13	7-10	7-8
Residual ash	2-3	7-12	15-28	7-7	15-20	26-33

Source: Winugroho (1981).

defined pattern. Temporal changes in the NDF mass of two stem internodes of wheat (S1, the topmost internode, and S5, a lower one) are shown in Figure 1. The main features were:

1. The lower internodes attained maximum NDF mass earlier than the upper ones;
2. After the point of maximum elongation, which for S1 was about 15 days after anthesis and for S5 about 20 days before anthesis, mass continued to increase, presumably due to cell wall thickening; and
3. Mass did not increase beyond about 4 weeks after anthesis.

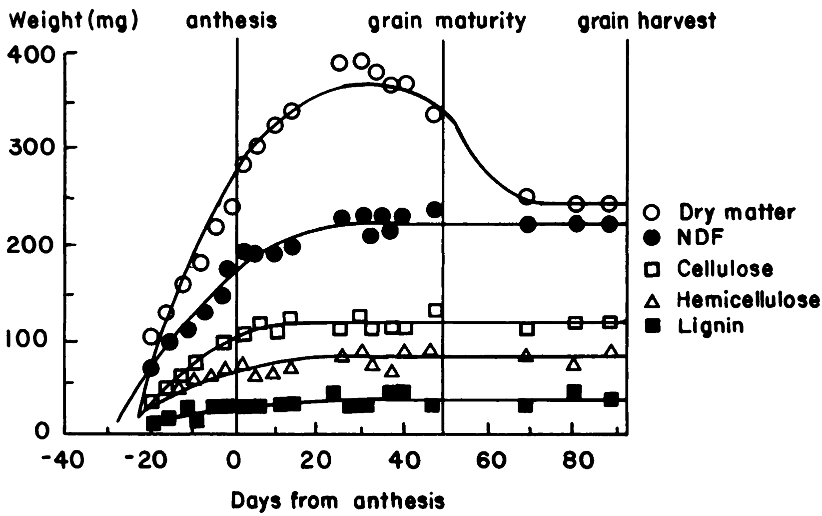
Figure 1. *Changes in mass of NDF in two internodes (S1, S5) of wheat.*



Source: G.R. Pearce (unpublished data).

Figure 2 shows changes in the mass of cellulose, hemicellulose and lignin in S2 over the same period. During growth, cellulose, hemicellulose and lignin are all being synthesised in the cell wall but the amount of cellulose deposited is greater than that of hemicellulose or lignin until after anthesis and beyond the point of maximum elongation. Synthesis of all three components stopped at the same time, about 4 weeks after anthesis. Between 20 days before anthesis and 30 days after anthesis, the amount of cellulose increased about 3.5 fold, the amount of hemicellulose about 2 fold and the amount of lignin about 5 fold (Figure 2). The pattern in the other stem segments was similar. This shows that manipula-

Figure 2. *Changes in mass of dry matter, NDF, cellulose, hemicellulose and lignin in S2 of wheat.*

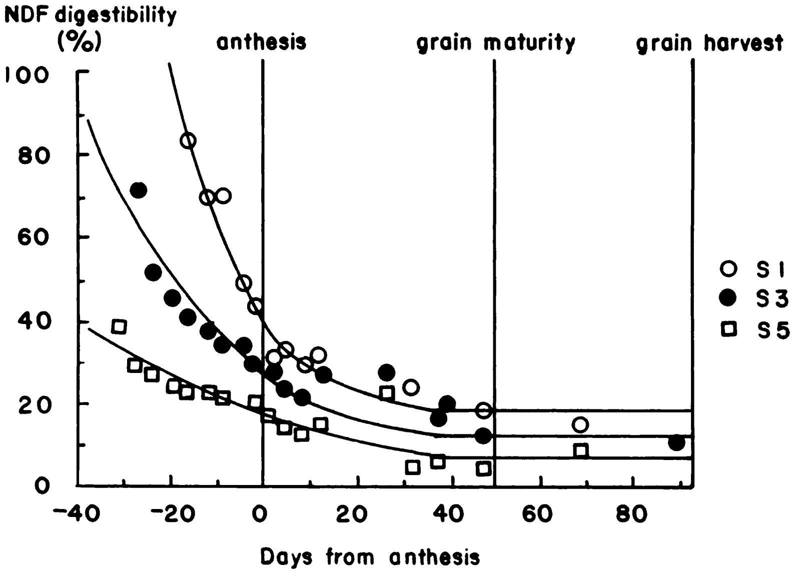


Source: G.R. Pearce (unpublished data).

tions of cell-wall composition to improve feeding value must focus on this period when rapid changes are occurring. In this case, manipulations would not have any effect if applied and expressed 4 weeks, or later, after anthesis.

These changes in chemical composition of stem internodes are reflected in *in vitro* NDF digestibility (NDFD) values (Figure 3). In the upper internodes, the decline in digestibility in the period immediately before anthesis was rapid and dramatic. For example, the NDFD of S1 fell by about 3.6% units per day and continued to decline until after anthesis. The changes in the lower internodes were earlier and slower than in the upper ones.

Figure 3. *Changes in NDF digestibility in three internodes (S1, S3, S5) of wheat.*



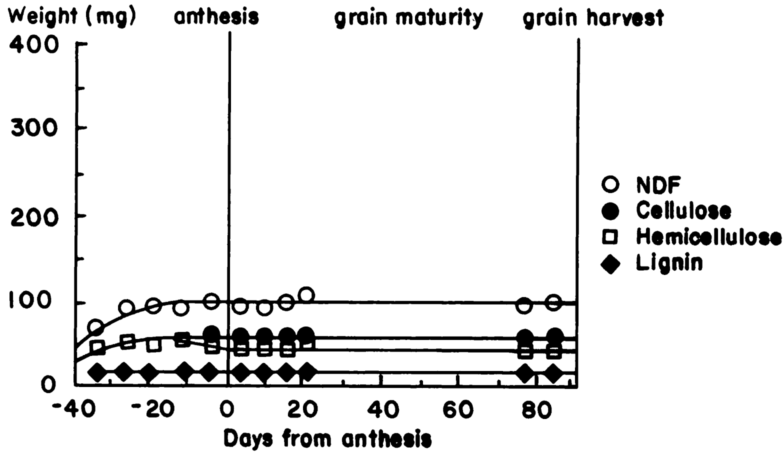
Source: G.R. Pearce (unpublished data).

Other results (J.A. Lee, unpublished data) have shown that NDFD and the digestibilities of cellulose and hemicellulose in the internodes of wheat decline at similar rates, but the final digestibility of hemicellulose was somewhat higher than that of NDF and cellulose. The similarity of the rates of change in digestibility for both cellulose and hemicellulose suggests that these components were affected similarly and equally by lignification and other factors associated with maturation and loss of digestibility.

The leaf blades and sheaths in the wheat examined by Lee were similar in mass and attained their maximal masses earlier than their corresponding internodes. In LS2 (Figure 4) and LB2 (Figure 5) maximal mass had been attained by anthesis. In LB2 there was an apparent loss of hemicellulose after anthesis, but there was no explanation for this. The NDFD of sheaths remained at about 40% beyond anthesis, while the NDFD of the blades continued to decline steadily but was still 50 to 60% in the straw.

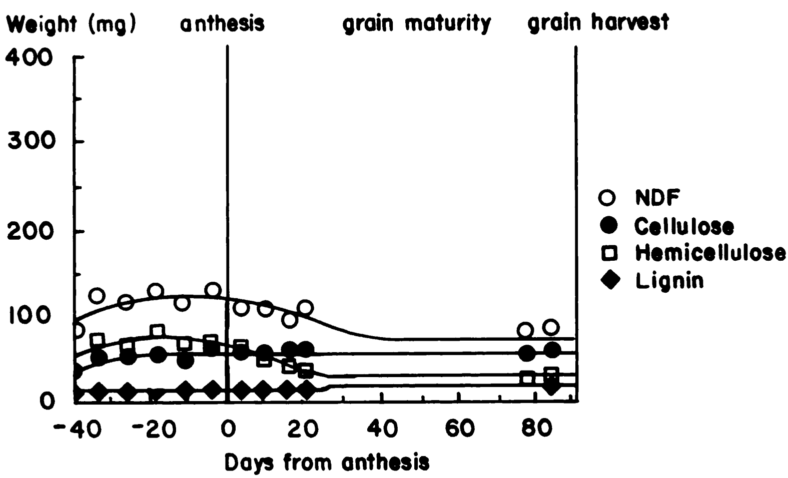
Cell-wall lignification is recognised as a prime cause of declines in digestibility but, often, only poor correlations have been obtained between lignin content and digestibility (e.g. Pearce, 1984). However, these have usually been between the percentage of lignin in the dry matter and dry-matter or organic-matter digestibility of whole straw. When the percentage of lignin in the NDF is correlated with NDFD for individual straw fractions, closer relationships may be obtained. For example the r^2 values for internodes, sheaths and blades were 0.94, 0.83 and 0.87, respectively, in exponential decay functions (J.A. Lee, unpublished data). For each relationship, the regression co-efficients were substantially different,

Figure 4. *Changes in mass of NDF, cellulose, hemicellulose and lignin in leaf sheath 2 of wheat.*



Source: J.A. Lee (unpublished data).

Figure 5. *Changes in mass of NDF, cellulose, hemicellulose and lignin in leaf blade 2 of wheat.*



Source: J.A. Lee (unpublished data).

indicating that a single regression from the pooled data, as is represented in whole straw, would be associated with wide variation and a lower r^2. Thus, the association of lignin with cellulose and hemicellulose is different in the three plant fractions and this must be taken into account.

Few attempts have been made to alter lignin synthesis in growing plants. However, at the University of Melbourne, treatment of annual rye-grass (*Lolium rigidum*) with gibberellic acid caused stem elongation and increased the proportion of lignin in the cell wall. The S1 contained 13% lignin in the NDF of the straw compared with 8% in untreated plants and the NDFD values were 17 and 26%, respectively. On the other hand, acute copper deficiency reduces lignin synthesis (Graham, 1976; Downes and Turner, 1986).

The relationship between cell-wall composition and digestibility deserves a continuing high research priority.

CELL CONTENTS

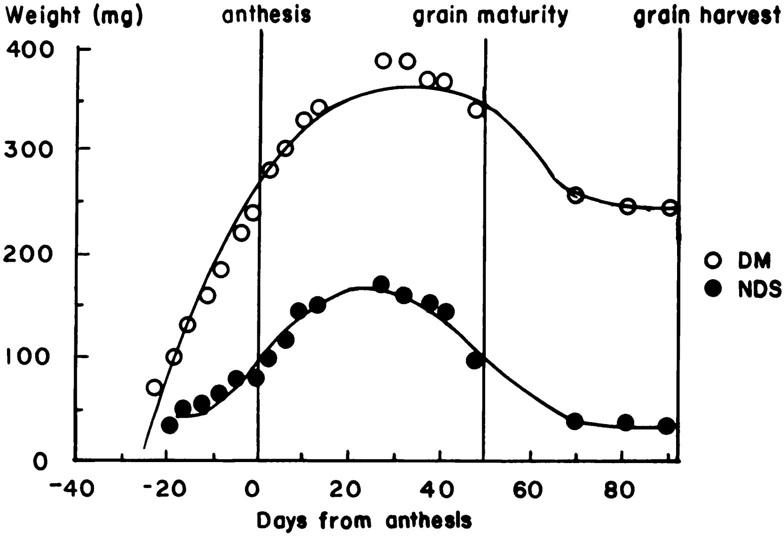
The cell contents comprise proteins, peptides and other nitrogen-containing compounds, carbohydrates, fats and minerals. These are removed effectively from plant tissues by neutral-detergent solution, except for starch which often requires further digestion with amylase for complete removal.

In senescing plants, fluctuations in NDS content are due mainly to changes in the amount of storage carbohydrates (fructans in wheat and starches in rice). The levels of storage carbohydrates retained in straw are critical to feeding value because of their high digestibility. The effects of changes in NDS in a senescing and dead internode of wheat on the digestibility of the internode are shown in Figures 6 and 7. NDS increased rapidly from shortly before anthesis and peaked about 4 weeks after anthesis (Figure 6). NDS digestibility was high throughout this period (Figure 7), as would be expected of a tissue enriched with soluble carbohydrates. Subsequently, the amount of NDS in the internode and NDS and organic/dry-matter digestibilities declined. Both the amount of NDS and its digestibility approached basal levels at the time of grain maturation.

The changes in the amount of NDS are associated with grain development in the following manner: Immediately after anthesis, photosynthates are produced in excess of requirements for grain growth because grain development is very slow. Grain mass increases rapidly from about 3 weeks after anthesis, consuming carbohydrates generated by current photosynthesis and, increasingly, from the mobilisation of storage carbohydrates in the culm (Blacklow et al, 1984). The contribution that reserve carbohydrates make to the final grain mass depends upon environmental conditions and perhaps upon genetic factors. If the plant is stressed the reserves will be drawn upon heavily by the grain. For example, in drought-stressed barley Gallagher et al (1975) found that 74% of the grain mass could be attributed to storage carbohydrates, whereas other reports (e.g. Evans and Wardlaw, 1976) have suggested as little as 10%.

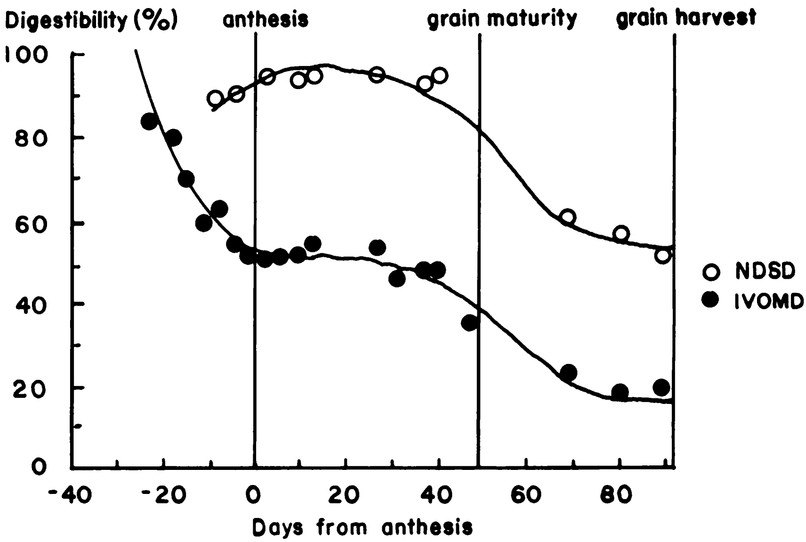
The extent to which, and the conditions under which, storage carbohydrates are respired are uncertain. Rawson and Evans (1971) estimated that

Figure 6. *Changes in mass of dry matter and neutral-detergent solubles in S2 of wheat.*



Source: G.R. Pearce (unpublished data).

Figure 7. *Changes in IVOMD and NDS digestibility in S2 of wheat.*



Source: G.R. Pearce (unpublished data).

30% of the fructans of wheat are used for respiration, but L.C. Incoll (personal communication) found that almost all C^{14}-labelled fructans in stems are mobilised to the grains, indicating that, at least during grain filling, fructans are most probably not used for respiration. Another possible loss is transport to the lower parts of the plant to support late tillering. In certain crops and particularly under conditions of high fertility and moisture (e.g. irrigation), late tillering can occur. In rice this is called "rattooning" and is sometimes used as a means of obtaining a second grain harvest.

NDS exhibits two main levels of digestibility; 90% when the stems are high in NDS and 40-50% when the stems are low in NDS, after they have senesced. It thus seems reasonable to consider NDS as being comprised of two pools of nutrients: (a) the intrinsic nitrogen compounds, carbohydrates, fats and minerals of the cytoplasm, mitochondria, membranes, nucleus, chloroplasts and other organelles, which, as a whole, are apparently less digestible in senescing and dead plant tissues, and (b) the reserve carbohydrates and proteins. Proteins are efficiently mobilised from senescing plant tissues and, except under conditions of high nitrogen fertilizer application (e.g. Roxas et al, 1985), their concentration in straw is low (Dalling, 1985). However, considerable amounts of storage carbohydrates, such as fructans in temperate grasses (Ojima and Isawa, 1968) and glucans and starches in rice, may be present in dead crop dry matter.

Different plant fractions do not store carbohydrates uniformly. Stems store considerably more than leaf sheaths, which store more than leaf blades. In wheat, the penultimate internode, S2, accumulates most fructans. In wheat, the upper parts of the culm contain larger proportions of NDS than the lower parts, as might be expected from their age, degree of senescence and proximity to photosynthesising leaves in the crop canopy. In irrigated rice, however, there may be no difference in the NDS content of the upper and lower parts of the straw (Hart and Wanapat, 1985; Winugroho, 1986).

The proportion of NDS in wheat straw ranges from 12% (W.J. Wales, unpublished data) to 41% (Ayres et al, 1976) of the dry matter and in rice straw from 14% (Cheva-Isarakul and Cheva-Isarakul, 1984) to 46% (Roxas et al, 1984). Higher values are associated with higher digestibility because of greater amounts of residual storage carbohydrates. In considerations of straw quality, therefore, the role of the storage carbohydrates is critical: the more storage carbohydrates remaining in straw the higher the digestibility. This has been expressed by Pearce (1984) as a high correlation between NDS% and IVOMD%. The pertinent question, therefore, is under what conditions are residual storage carbohydrate levels high in straw? The answer lies in the interactions between the photosynthetic activity of the plant at critical time periods and the demands of the grain.

The first requirement for high levels of storage carbohydrates is a high level of accumulation during the period around anthesis and for some time afterwards. For wheat in southern Australia this period spans about 40 days, from about 10 days before anthesis to about 30 days afterwards. Storage carbohydrates accumulate during this period if conditions are favourable for photosynthesis, i.e. suitable light and temperature conditions, adequate nutrient and water availability and the absence of disease. Thus, the history of the plant in terms of soil fertility, fertilizer application, spacing of plants and leaf development up to this time may be important.

The full extent to which storage carbohydrate accumulation varies is not known but, under a range of conditions at the University of Melbourne, amounts of NDS in stem segments varied widely. For example, among five different, but related, wheat cultivars grown side-by-side in the same season, NDS content of the S2 at peak accumulation ranged from 114 to 280 mg. The NDS content of S2 of plants grown under normal field conditions peaked at 158 mg, compared with only 60 mg for the same cultivar grown under apparently favourable conditions in pots in a glasshouse (W.J. Wales, unpublished data). Ambient temperatures and rates of growth relative to crop photosynthetic activity may all have an effect on the accumulation of carbohydrate reserves. Under field conditions in Western Australia, M. Nicolas (personal communication) has concluded that wheat cultivars do, however, vary widely in their ability to accumulate fructan reserves.

The second requirement for high levels of storage carbohydrates in straw is a low rate of removal. Normally, developing grains draw on storage carbohydrates to augment the metabolites provided by current photosynthesis. As current photosynthesis declines during senescence the reserves are drawn upon. If current photosynthesis is optimal then the extent to which reserves are used depends largely on the number of grains developing, i.e. the size of the "sink". If there are few grains levels of storage carbohydrates and straw quality are more likely to be high. However, correlation between grain yield and straw quality is often poor (e.g. Erickson et al, 1982), partly because of the variable accumulation and loss of storage carbohydrates.

Where the sink is small, mobilisation of storage carbohydrates may be delayed and reduced if sufficient moisture and nutrients are available for the crop. This may happen under irrigation but in dryland situations seasonal constraints are likely to predominate.

At this stage, it is only possible to conclude that the relationships between the amounts of residual storage carbohydrate in straw and other physiological events involved in yield formation in crops are likely to be complex. However, an understanding of these interactions may identify opportunities for manipulation of carbohydrate reserves so as to achieve high-quality straw for animal production without significant reductions in grain yield and quality.

ANIMAL FACTORS INTERACTING DIRECTLY WITH STRAW CHARACTERISTICS

Straw intake and digestibility in ruminants are influenced by straw characteristics (including chemical composition, morphological and anatomical features, physical nature and palatability); by feeding conditions (including the amount offered and the frequency of feeding); and by animal characteristics (including species/genotype, liveweight, age, body condition, type and level of production and disease). Extremes of temperature and humidity and social interactions between animals may also affect intake. Reviews on herbage digestibility (e.g. Akin, 1982) and intake (e.g. Armstrong, 1982) have discussed the principles involved, but without specific reference to straws. A major limitation is the small number of experiments in which animals have been fed straw alone; the diet has usually been supplemented with nitrogen and minerals and, often, energy. The following discussion is limited to specific aspects that are particularly relevant to straws.

Selection in relation to physical characteristics of straws

Weston (1985) included texture as a criterion governing acceptability of feeds and Hogan et al (1986) suggested that animals select plant material on the basis of "tenderness." However, such characteristics are difficult to assess because, often, no one feature predominates and several factors interact. In straws, such as wheat (Doyle et al, 1987) and barley (Wahed and Owen, 1986) animals usually show a preference for leaves rather than stems. Where such preference is shown, useful comparisons between many literature reports are almost impossible because of the lack of information on feeding procedures and because of unspecified degrees of selection, especially when straws have been offered in excess of appetite.

In rice straw, selection of leaves in preference to stems may not occur (Doyle et al, 1987), possibly because the leaf blades contain more silica than the stems (Doyle et al, in press), as suggested by Van Soest (1982).

Resistance to particle size reduction

If the plant material is highly resistant to particle size reduction voluntary intake will be reduced because large particles of digesta cannot pass through the reticulo-omasal orifice into the lower digestive tract. Thus, large particles are retained in the reticulo-rumen until they are broken down by rumination or detrition. The comminution of feed particles during chewing also contributes to this process. Lee and Pearce (1984) found that, in five roughages, including barley and oat straw, chewing by cattle reduced about 50% of the material to particles that would pass through a 1 mm screen.

The extent and rate of particle size reduction is not the only mechanism controlling roughage intake and the rate at which digesta leave the reticulo-rumen is not necessarily proportional to feed intake because (a) the amount of digesta in the reticulo-rumen can vary and (b) the rate and extent of fermentation varies according to the available nutrient content of the roughage. Thus, straws of differing composition would be expected to produce differences in fermentation kinetics. However, the full details of the system have not been resolved.

Grinding energy has been used as an index of resistance to particle size reduction. This is the amount of electrical energy required to grind 10 g of feed through a 1 mm screen (Chenost, 1966; Foot and Reed, 1981). In wheat straws, the grinding energy of leaf blades is lower than that of leaf sheaths which is lower than that of stems, but in rice straw the differences may not be as great (Table 8). In experiments with wheat straw (W.J. Wales, unpublished data) and with rice

Table 8. Grinding energy (J g^{-1} DM) of wheat and rice straw fractions (averages from three straws).

Fraction	Wheat straw	Rice straw
Leaf blade	83	100
Leaf sheath	122	103
Stem	213	147

Segments were chopped into 2 cm lengths prior to grinding.
Source: Doyle et al (in press).

straws (Chanpongsang, 1987), good inverse relationships were obtained between intake by sheep and grinding energy within cereal species but not between species (Table 9). Other factors, including possibly silica content, are thus involved.

Table 9. Intake, grinding energy and rate of eating for three wheat and three rice straws.

	Wheat straw			Rice straw		
Measurement	1	2	3	1	2	3
Intake (g OM d^{-1})	617	484	303	492	383	369
Grinding energy (J g^{-1} DM)	138	161	195	95	109	107
Rate of eating (g air dry h^{-1})	516	434	287	386	309	269

Sources: W.J. Wales (unpublished data); Chanpongsang (1987).

Eating rate

Eating rate has been used to evaluate herbage quality. Table 9 shows positive relationships between intake and eating rate of wheat and rice straws. These measurements were made with trained sheep and reflected characteristics of the feeds associated with palatability or acceptability. With wheat straw, material with a high proportion of stem is eaten much more slowly than leafy material. Habituation is also a factor, because straws that are eaten relatively slowly in early tests may be eaten more quickly in later tests. This occurred particularly with rice straws in which, it is believed, silica levels may have affected acceptability initially. The specific plant causes of such animal responses are unknown.

Metabolic factors influencing intake of straws

Voluntary intake of highly digestible forages is controlled by metabolic factors or is linked to requirements for maintenance and production. In the case of poorly digestible materials, however, attention has been focused on physical control of intake, particularly distension of, and removal from, the reticulo-rumen. However, the amounts and balance of nutrients supplied by low-quality straws are so limiting that metabolic contributions to the control of intake should not be overlooked.

Doyle et al (1987) concluded that, in view of the relatively small amount of digesta in the reticulo-rumen of animals fed unsupplemented straws, the purely physical control mechanisms do not operate or the levels at which the system is sensitised are lower, due perhaps to nutrient imbalances in the tissues. In either case, an extremely complex set of interactions determines intake levels. The kinetic features of digestion for straws with varying proportions of nutrients and for straws which are supplemented to provide limiting nutrients are variable.

CONCLUSIONS

In this paper, attention has been directed towards the characteristics of the cell wall and cell contents as they determine the nutritive value of cereal straws, and reference has been made to some other factors directly affecting intake and digestion of straws by animals. Because of differences between morphological fractions of plants, only limited information can be obtained from assessments of whole straws. Different harvesting, threshing and feeding practices, which affect the proportions of the main morphological fractions, will determine the nutritive value of the straw actually consumed by animals.

Cell-wall digestibility can be improved by chemical and other treatments but such procedures are too expensive for wide practical application. The alternatve, separating material with high digestibility (e.g. leaf blades in wheat) from material with low digestibility (e.g. stems in wheat), is also expensive and suffers from the disadvantage that the less digestible fraction usually forms the largest proportion of a crop residue. Breeding for greater leafiness may also not be attractive because this would lower the harvest index.

The main factor determining the digestibility of cell-wall material is lignin, but the precise limiting role of lignin is still unresolved. The information presented in this paper indicates that lignification effects need to be studied in discrete plant tissues. Identification of periods during which cell-wall digestibility is changing rapidly probably provides the best opportunity to understand the significance of concurrent chemical changes. The thrust of agronomic or genetic manipulations to alter cell wall characteristics must await a clearer understanding of lignin chemistry in relation to other cell wall constituents.

The potential contribution of the cell contents to the nutritive value of straws appears to have been under-estimated in the literature. Not only can straws contain quite large proportions of cell contents, but the amount of storage carbohydrates in the cell contents can vary widely. Because storage carbohydrates are highly digestible (probably 100%), they may have a marked effect on the nutritive value of straws. In this paper, the pattern of accumulation and subsequent removal of solubles in wheat stem internodes has illustrated the means by which varying amounts of storage carbohydrates remain in straws. However, the precise mechanisms involved have not been elucidated. Complex interactions occur between storage carbohydrate metabolism and other physiological processes in the plant, mediated by environmental and genetic factors. Only an understanding of these will permit genetic improvement of straw quality without reducing grain yield and quality.

Factors in straws that impinge directly upon an animal's senses, thus influencing its level of intake, have not been studied in detail, partly because straws have rarely been fed without supplementation. It is clear, however, from the available results that important differences may occur. To date, these have been monitored as differences in features such as grinding energy, eating rate and chemical composition, but alone or collectively they may result in pronounced differences in voluntary intake by animals, often associated with high degrees of selection for certain plant parts. The precise plant features that are responsible and the variation between animals in response to these have not been defined. Again, an understanding of these is necessary so that appropriate manipulations, by genetic or other means, may be approached.

ACKNOWLEDGEMENTS

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DISCUSSION

Van Soest: I am pleased to see the relationship between the cell walls and the lignin. How did you measure the digestibility of the neutral-detergent solubles and what is the indigestible fraction?

Pearce: We measured neutral-detergent solubles as 100% minus the neutral-detergent fibre. We measure the NDF before we start and the NDF of the residue and 100-NDF is the indigestible neutral detergent solubles.

Van Soest: Is this after cellulase digestion?

Pearce: Yes, after pepsin-cellulase.

Van Soest: There might be fractions in there that might be digestible by other enzymes. Is that possible?

Pearce: Such as what?

Van Soest: Such as pectins, galactans, soluble hemicelluloses or phenolics.

Pearce: There is not much pectin in wheat straw. How else can we measure the digestibility of neutral-detergent solubles?

Van Soest: The Lucas test on straw indicates that the neutral-detergent solubles have a 90% plus true digestibility and wheat straw follows that relationship in animal digestion trials.

Pearce: Yes, although I am not convinced about that. It is quite plausible that, in the absence of soluble carbohydrates, the cell contents are not completely digestible. Chloroplasts are probably undigestible and membranous materials and nucleus residues are only 20% digestible.

Uden: I think the difference between the animal work and the cellulase work is that you can never tell the digestibility of the neutral-detergent solubles *in vivo*. A lot of soluble compounds are excreted in the urine. Chesson has found low digestibility of chloroplasts and other organelles in the cell solubles.

Pearce: Yes, it's impossible to get an estimate of digestibility of neutral-detergent solubles because of all the material that is added on the way through the digestive tract.

Thomson: You made the comment that you should try to have more cell contents in the straw. How will that affect grain yield?

Pearce: Under favourable conditions the grain does not rely very much on the stored fructans in wheat. I am not suggesting that we need to retain all the fructans, why not use enough for the grain and save the rest? We need to reduce wastage by respiration in the senescing plant. On the other hand, if the plant is stressed during grain development, it might be detrimental.

FACTORS AFFECTING THE NUTRITIVE VALUE OF SORGHUM AND MILLET CROP RESIDUES

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INTRODUCTION

Sorghum (*Sorghum bicolor*) and pearl millet (*Pennisetum typhoides*) are the most important food crops in the semi-arid, drought-prone areas of Africa. Over 10 million tonnes of grain from each cereal are produced annually, 95% of which is used for human food (Hulse et al; 1980).

Sorghum and millet crop residues are an important potential feed resource. In 1981, 55.2 and 51.4 million tonnes of crop residue were produced from sorghum and millet respectively (Kossila, 1985). Assuming a digestibility of 45% and 20% wastage, the annual maintenance requirements of 39 million tropical livestock units (250 kg liveweight) could be met by sorghum and millet crop residues supplemented with low-levels of protein or non-protein nitrogen. However, to raise productivity above maintenance, digestibility and protein supplementation would need to be increased.

Livestock are an important component of agricultural systems in the semi-arid regions of Africa. They are an important source of income and a means of saving capital for use in times of need. Under conditions of improved productivity, livestock may serve as a catalyst to increase overall farm productivity. Ruminant livestock can complement crop production by increasing soil fertility through manure, by providing traction for cultivation, by grazing areas that can not be cultivated and by using crop residues for feed. However, poor nutrition is a major constraint to increased livestock productivity. Feed is often in short supply and nutritive value low. Grazing and crop residues are low in protein and energy and may also be deficient in important mineral nutrients.

Improved livestock feeding systems need to be developed for the smallholder farmer of Africa who depends on millet and sorghum for subsistence. Although these cereals are a staple food crop, they have low economic value during years of average and above average rainfall. The stability and overall productivity of farming systems could be improved by the introduction of livestock rearing activities that combine efficient use of crop residues with forage legumes and multi-purpose trees.

Although much research has been devoted to upgrading straw by chemical treatment (Jackson, 1978), little attention has been given to variation in the nutritive value of untreated crop residues as influenced by variety and environment. Quantity and quality of cereal crop residues are important criteria in a farmer's decision to grow a particular variety. Varietal and environmental effects on the nutritive value of cereal crop residues are also important. The nutritive value of residues from a given variety varies widely due to differences in growing conditions (season, elevation or latitude). High temperature during growth increases cell wall and lignin contents and decreases digestibility (Deinum, 1976). High humidity and rain during and after grain harvest reduce nutritive value. Loss of leaves through wind or trampling of cereal crop residues left in the field also causes deterioration. These losses can be reduced by improved conservation practices.

It is well known that cereal crop residues are deficient in protein. However, supplementation with non-protein nitrogen or protein does not always increase intake and digestibility because other factors limit nutritive value. These factors need to be determined because, within the range of energy intake of cereal crop residues, large increases in animal productivity can be achieved by relatively small increases in digestibility and intake.

Cell wall, as estimated by neutral-detergent fibre, accounts for as much as 80% of the dry matter in cereal crop residues and represents a large source of energy for ruminants. However, the ability of rumen micro-organisms to digest cell wall polysaccharides (cellulose and hemicellulose) is limited by the presence of phenolic and other aromatic compounds which are generally referred to as lignin. The phenolic constituents of sorghum and millet have been subject to little investigation. However, the digestibility of the crop residues will be correlated with the nature and amount of phenolics associated with their cell walls and the influence of environment on phenolics (Hartley, 1981).

SORGHUM

In Africa, birds are a major crop pest and limit grain production from sorghum (Bullard and Elias, 1980). Bird resistance is related to the amount of proanthocyanidins (condensed tannins) in the grain (Gupta and Haslam, 1980). Sorghum improvement programmes in Africa are breeding for bird resistance in varieties for semi-arid zones. The phenolic content of the vegetative components of bird resistant (BR) and forage varieties is negatively associated with digestibility (Saini et al, 1977; Cummins, 1971). Weanling rats fed a diet containing leaves from BR varieties had lower feed efficiency and N retention than those fed a diet containing leaves from non-bird-resistant (NBR) varieties (Gourlay, 1979). In this section the differences between BR and NBR varieties in content of phenolics and their relationship to digestibility of fibre in the crop residue are discussed.

BR and NBR varieties do not differ in their N or neutral-detergent fibre (NDF) contents and leaves contain twice as much N as stems (Reed et al, 1987). The total cell wall as estimated by NDF is greater than 70% of the organic matter in sorghum leaves. Silica is also a cell wall component (Jones and Handreck, 1967), but is not completely recovered in the NDF. Silica content of sorghum leaves (9 to 15% of the dry matter) is much higher than that found in temperate forages and most other cereal crop residues (Reed et al, 1987).

Most of the energy obtained by ruminants fed sorghum crop residues comes from rumen fermentation of cell wall carbohydrates. Factors that limit the digestibility of these carbohydrates would have the greatest influence on differences in nutritive value between varieties after N deficiencies are corrected. Leaf blades and leaf sheaths from BR varieties have higher levels of insoluble proanthocyanidins and soluble red pigments than those of NBR varieties (Table 1). Leaf sheaths from BR varieties are higher in lignin than those from NBR varieties.

In leaves and stems, linear correlation coefficients among insoluble proanthocyanidins, soluble red pigments and soluble phenolics as measured by absorbance are positive and significant (Table 2).

Leaves and stems from BR varieties contain red pigments that are extracted by polar organic solvents. However, NDF from BR varieties, prepared by sequential extraction with aqueous acetone and neutral-detergent, is also red. Red pigmentation, as measured by absorbance of insoluble proanthocyanidins at 550 nm, is associated with larger amounts of lignin in BR varieties (Figure 1).

In leaves, lignin, insoluble proanthocyanidins and soluble red pigments contents are negatively correlated with extent of NDF digestion and digestibility of NDF at 48 hours, and positively correlated with indigestible NDF (Table 3). Insoluble proanthocyanidins and soluble red pigments contents are negatively correlated with rate of NDF digestion.

Phenolics are a major factor limiting digestibility of NDF in leaves. BR varieties are higher in phenolics than NBR varieties. Digestibility of NDF at 48 hours is an important parameter because it is used to estimate *in vivo* digestibility

Table 1. The effect of site and bird resistance on content of neutral detergent fibre (NDF), digestibility of NDF (DNDF), content of lignin, soluble red pigments (A550 sol.) and insoluble proanthocyanidins (A550 insol.) in leaf blades, leaf sheaths and stems from the crop residue of bird resistant (BR, n=6) and non-bird-resistant (NBR, n=8) sorghum varieties.

	Debre Zeit				Melkasa					
	BR		NBR		BR		NBR		Significance	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Site	Resist.
Leaf blades										
NDF (% OM)	62.3	3.4	64.6	3.2	60.6	3.2	60.0	3.2	**	NS
DNDF (%)	57.1	4.2	61.5	3.8	62.4	5.5	61.9	4.5	**	NS
Lignin (% OM)	3.5	0.4	4.2	0.6	4.2	0.6	4.0	0.6	NS	NS
A550 sol.	0.08	0.02	0.05	0.01	0.16	0.07	0.07	0.02	***	***
A550 insol.	0.04	0.01	0.04	0.01	0.09	0.07	0.06	0.05	NS	NS
Leaf sheaths										
NDF (% OM)	79.1	2.3	79.4	1.5	77.0	2.9	78.3	2.6	NS	**
DNDF (%)	51.2	3.8	56.6	2.6	42.8	10.1	55.3	5.3	***	*
Lignin (% OM)	6.3	0.9	5.7	0.5	6.1	0.8	5.8	0.7	***	NS
A550 sol.	0.14	0.05	0.03	0.01	0.57	0.20	0.05	0.03	***	***
A550 insol.	0.04	0.01	0.02	0.01	0.19	0.11	0.03	0.02	***	***
Stems										
NDF (% OM)	72.2	7.4	74.5	5.5	78.4	6.2	79.8	3.3	***	**
DNDF (%)	52.9	5.6	54.1	3.9	57.4	5.0	57.0	4.7	**	NS
Lignin (% OM)	6.8	1.4	7.0	1.3	6.7	1.1	6.6	0.8	NS	NS
A550 sol.	-		-		-		-		-	-
A550 insol.	0.03	0.01	0.02	0.01	0.01	0.00	0.01	0.00	***	***

NS=not significant; **=P<0.01; ***=P<0.001.

Table 2. Linear correlation coefficients among lignin, insoluble proanthocyanidins, soluble red pigments and soluble phenolics as measured by absorbance at 280 nm (A280) in leaves and stems from 24 sorghum varieties.

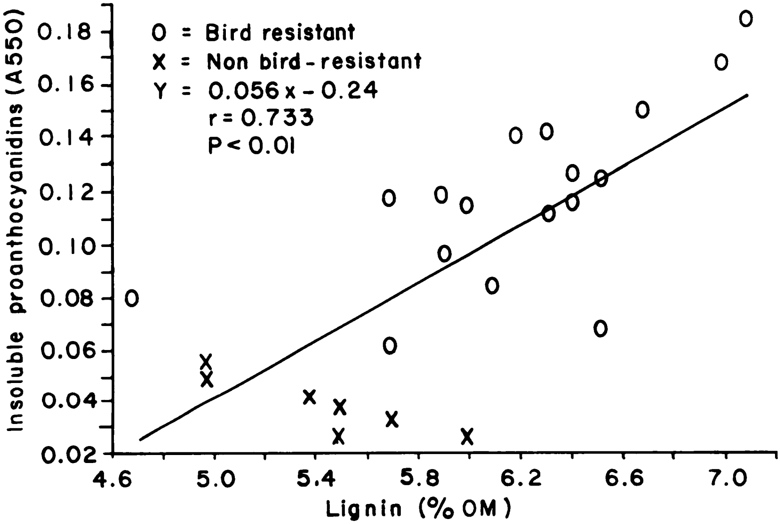
	Lignin	Insoluble proantho-cyanidins	Soluble red pigments
Leaves			
Insoluble proanthocyanidins	0.733**		
Soluble red pigments	0.762**	0.917**	
Soluble phenolics	0.446*	0.457*	0.599**
Stems			
Insoluble proanthocyanidins	0.286		
Soluble red pigments	0.390	0.826**	
Soluble phenolics	0.401	0.726*	0.909**

Source: Reed et al (1987).
* P<0.05.
** P<0.01.

(Goering and Van Soest, 1970). Phenolics (lignin and insoluble proanthocyanidins) accounted for most of the variation in digestibility of NDF at 48 hours in leaves (Figure 2).

Environmental factors have a large effect on pigmentation in sorghum leaf blades and sheaths. BR varieties grown at Melkasa (elevation 1500 m)

Figure 1. *Relationship between lignin and insoluble proanthocyanidins contents of leaves from the crop residue of bird-resistant and non-bird-resistant sorghum.*



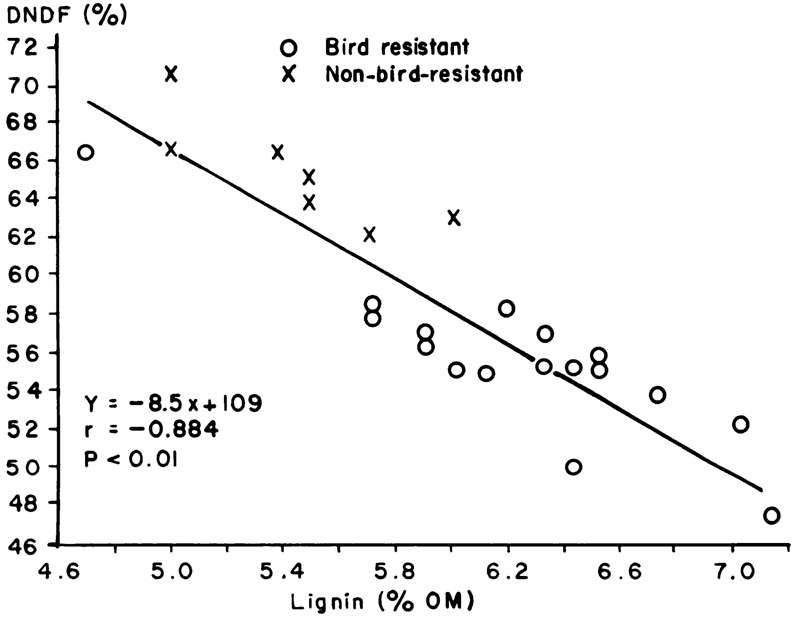
in the Ethiopian Rift Valley had greater pigmentation in blades and sheaths than the same varieties grown at Debre Zeit at higher elevation (1800 m). The effects of these phenolic pigments on NDF digestibility was greatest in leaf sheaths from BR varieties grown at Melkasa (Table 1). Average maximum temperatures during the growing season at Melkasa were 2 to 3^{o} C higher, and average minimum temperatures 5 to 7^{o}C higher, than at Debre Zeit. Total rainfall during the growing season was 645 mm at Melkasa and 693 mm at Debre Zeit. The mean digestibility of leaf sheaths from BR varieties grown at Melkasa was 8.4 percentage units lower than that of the same varieties grown at Debre Zeit and over 12 units lower than that of NBR varieties grown at either site (Table 1). These

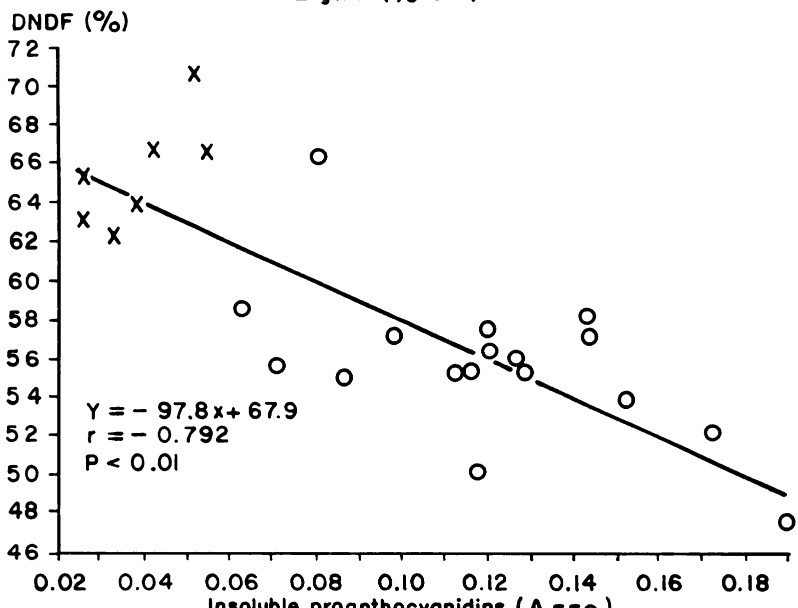
Table 3. Linear correlation coefficients between parameters of digestibility of neutral-detergent fibre (NDF) and lignin, insoluble proanthocyanidins, soluble red pigments and soluble phenolics as measured by absorbance at 280 nm in leaves and stems from 24 sorghum varieties.

	Potentially digestible NDF	Rate of NDF digestion	Indigestible NDF	NDF digestion at 48 h
Leaves				
Lignin	-0.784**	-0.248	0.808**	-0.884**
Insoluble proantho-cyanidins	-0.525**	-0.518*	0.520*	-0.797**
Soluble red pigments	-0.553**	-0.493*	0.623**	-0.846**
Soluble phenolics	-0.542**	-0.195	0.491*	-0.603**
Stems				
Lignin	0.270	-0.099	0.759**	-0.364
Insoluble proantho-cyanidins	0.390	0.222	0.067	0.361
Soluble red pigments	0.410	0.295	0.214	0.366
Soluble phenolics	0.362	0.247	0.270	0.249

* $p<0.05$.
** $p<0.01$.

Figure 2. *Relationship between digestibility of neutral-detergent fibre (DNDF) and lignin and insoluble proanthocyanidins in leaves from the crop residue of bird-resistant and non-bird-resistant varieties of sorghum.*





results suggest that phenolic pigments have their greatest effect on leaf sheath digestibility and that environmental effects may also be greatest on this plant fraction.

In stems, there is a significant correlation between lignin content and indigestible NDF but no correlation between lignin content and digestibility of NDF at 48 hours (Table 3). Lignin may be more unevenly distributed in stems than in leaf blade and sheaths. The amount of lignified tissue may determine the amount of indigestible NDF in relation to different proportions of rind and pith. Soluble red pigments and insoluble proanthocyanidins contents are lower in stem than in leaves, suggesting that these phenolics are less important in the digestion of NDF in stems (Reed et al, 1987).

The range in NDF digestibility in leaves and stems from sorghum crop residue is large. The amount of phenolics in leaves accounts for most of the variation in digestibility. Leaves are more important than stems in determining nutritive value because of their greater N content and greater consumption by livestock (Powell, 1984). BR varieties have a higher phenolics content than NBR varieties. These relationships indicate that breeding for bird resistance in sorghum lower the nutritive value of the crop residue. However, some varieties may have bird-resistant grain and low phenolic content in the crop residue. Such varieties may be useful in farming systems in semi-arid areas of Africa where birds are an important pest and the crop residue is an important feed.

Five sorghum varieties, selected on yield criteria, were used to determine the effect of variety on intake and digestibility of the crop residue in mature highland zebu oxen. After grain harvest, the crop residue from each variety was coarsely chopped and fed to five oxen in a latin square design. Oxen were offered 12 kg of crop residue dry matter per day. This diet was supplemented with 60 g of urea added to the drinking water.

Daily dry-matter intake varied by more than 1 kg among varieties (Table 4). The variety with the lowest intake (MW5020) is a dwarf, bird-resistant variety which gives high grain yield but little residue. MW5020 had the highest proportion of leaves in the crop residue but its leaves were strongly pigmented. It was the only variety with a measurable amount of leaf in the feed refusals. The intake of digestible energy from MW5020 would be adequate for maintenance requirements only, whereas the intake from Melkamash and 5DX 160 would allow weight gains of over 200 g per day.

Table 4. The effect of sorghum variety on intake of crop residue by highland zebu oxen.

Variety	Percent leaves	Mean intake (kg day^{-1}) (n=5)
MW5020	43.7	4.11a
Buraihi	23.2	4.43a
2KX17	37.9	4.90b
Melkamash	39.3	4.96b
5DX-160	35.3	5.18b

Means with different superscripts are significantly different ($p < 0.05$).

MILLET

Variety had a significant effect on NDF content and NDF digestibility in blades, sheaths and stems from 12 millet varieties (Table 5), and on lignin content in blades and stems. The millet varieties were sampled from an advanced agronomic trial at the ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) Sahelian Center, Sodore, Niger.

Table 5. The effect of variety on content of neutral-detergent fibre (NDF), digestibility of NDF (DNDF) and content of lignin in leaf blades, leaf sheaths and stems from the crop residue of 12 millet varieties.

	Mean	Range	Varietal effect
Leaf blade			
NDF (% OM)	59.9	57.7-63.0	**
DNDF (%)	60.1	55.7-62.2	***
Lignin (% OM)	3.9	3.5- 4.5	**
Leaf sheath			
NDF (% OM)	69.2	65.5-70.8	**
DNDF (%)	42.4	38.1-44.9	***
Lignin (% OM)	5.1	4.8- 5.9	NS
Stem			
NDF (% OM)	76.2	72.5-79.6	**
DNDF (%)	30.7	27.6-35.2	*
Lignin (% OM)	8.7	7.6- 9.7	***

Varietal effect significant at: * P<0.05; ** P<0.01; *** P<0.001; NS not significant.

Although varietal effects were significant, the range in parameters of nutritive value among varieties is lower than among sorghum varieties. The range in NDF digestibility within sorghum plant parts is greater than 15 percentage units (Figure 2), whereas in the 12 millet varieties tested the range was less than 8 percentage units (Table 5). Millet lacks the phenolic pigments that have a large effect on NDF digestibility in BR sorghum varieties.

The digestibility of NDF in the leaf sheath and stem fractions of the 12 millet varieties was low. Varieties with higher digestibility and adaptation to the Sahel need to be sought.

CONCLUSIONS

Crop residues will continue to be important feed resources in developing countries and increased ruminant production can be accomplished through improved utilisation of the crop residues from sorghum and millet. Dairy producers in many urban areas of India depend on these crop residues as the major source of roughage. They are supplied by smallholder farmers at organised fodder markets and sale of crop residue can account for more than 50% of total income from crops (Parthasarathy Rao, 1985). These dairy enterprises are meeting the increased demand for milk and milk products in urban areas of India (Walker, 1987).

Similar ruminant production systems exist around urban areas in Africa. More efficient utilisation of sorghum and millet crop residues could contribute to increased productivity and income for both livestock producers and smallholder farmers. Crop improvement programmes could improve these systems by developing crop varieties that are suitable for dual purpose production of both grain and fodder.

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DISCUSSION

Berhane: What are the implications for a plant breeding programme when temperature has such a large effect on pigmentation and digestibility?

Reed: We need to look for low pigmented, bird-resistant cultivars. Pigmentation varies considerably among bird-resistant cultivars but this is also heavily influenced by environment, which could lead to genotype by environment interactions. We could score blade pigmentation at various sites; this could easily be incorporated into bird-resistance trials.

Berhane: You singled out one variety which was bird resistant and was high in tannin and high in digestibility. Was that variety incorporated in animal feeding trials?

Reed: I cannot recall if we used this variety in our feeding trials. The variety that had the highest intake in the oxen trial was selected because of the high digestibility of its stems, which indicates that stem digestibility may be a major factor determining the nutritive value of sorghum. This variety was also bird resistant.

Ørskov: What is the correlation between stem, blade and sheath digestibility?

Reed: The correlation was very poor in our data on sorghum.

Pearce: In ryegrass the correlation is quite good: if stem is highly digestible, the sheath and blade will also be highly digestible.

Capper: We looked at botanical fractions in sorghum at ICRISAT. When you plot these against height, over the range of 150 to 300 cm there is little change in the proportion of botanical fractions, but below 150 cm the amount of leaf sheath, which is the least digestible fraction and in which there was the most variation in digestibility, starts to increase quite rapidly. If plant breeders breed for shorter varieties, the amount of less-digestible leaf sheath could become very significant. We found that leaf blade and stem have virtually the same digestibility. As suggested, the proportion of leaf sheath has the greatest effect on the nutritive value of sorghum.

Reed: The proportions of plant parts means nothing to a farmer who will feed coarse stovers. The amount of crop residue and the amount of a fraction that can be fed are more important. As such, we should also express our results in yield of the different components per hectare, which may give different relationships. For example, in our trials, medium-height varieties gave a much higher yield of leaf than dwarf varieties, despite having a smaller proportion of leaf in the straw. If you are feeding animals you may want the quantity, not the proportion, except if you were to grind the entire residue and feed it. But when grazed in the field, the leaf fractions are preferred and are of higher nutritive value.

SESSION 3

THE EFFECT OF GENOTYPE AND ENVIRONMENT ON THE NUTRITIVE VALUE OF CROP RESIDUES

General discussion

McDowell: The four papers presented in this session emphasised methodology and genetic and environmental effects on the nutritive value of crop residues. We should focus our discussion on how the methods relate to specific types of residue rather than on the relative merits of the different methods. We heard yesterday about the quantity and potential of crop residues but very little on the effect of environment on the nutritive value of crop residues.

Berhane: Has any high-yielding variety been rejected because of low straw quality?

Ørskov: No, I do not think so because it is only in the last few years that we have realised that there are large differences in straw nutritive value among varieties.

Fussell: In India, a high-yielding millet variety, WC75, had a better acceptance because it had better straw quality.

Gupta: WC75 is improved material from an introduction from Nigeria. We just heard that pearl millet in West Africa, especially Niger, is not accepted by cattle because of poor quality of the stems. However, similar material is used by farmers in India as stored cattle feed. This could be due to cultural differences and not because of the crop. We should not generalise that millet is not a good crop for feeding animals on crop residues.

Reed: The difference between West Africa and India in the use of millet crop residue may be related to cultural differences, but we cannot rule out the possibility of differences in nutritive value. In groundnuts, there is a large difference in the incidence of foliar diseases and their effects on the nutritive value of the crop residue. ICRISAT is breeding for resistance to foliar diseases in groundnuts and this would increase the quality of crop residue by reducing leaf loss. Groundnuts normally retain leaves in the absence of foliar diseases and the nutritive value of the crop residue can be very high.

McAllan: Reed showed differences in digestibility of sorghum grown at different sites and suggested that temperature was important. Barry, in Australia, grew lotus in two areas and the tannin content was markedly higher in the lotus grown on low-fertility soil. Has any work been done on the effect of soil fertility in sorghum?

Reed: I cannot eliminate soil fertility as a factor, although we applied N and P at moderate levels at both sites. Trace elements or soil pH could have had an effect. Certainly temperature and soil effects are important and lead to genotype by environment interactions.

McAllan: It is not surprising that we find large variation in nutritive value within a species if all these conditions are not controlled. How can you breed for something you do not know how to control?

Reed: Pigmentation is a genotypic characteristic. Some genotypes respond by producing greater pigmentation, others do not respond. The non-bird-resistant varieties do not produce the pigmentation and the difference between the sites was very low.

Pearce: Plants respond to differences in soil fertility by altering their rate of growth. Slow-growing plants tend to accumulate more secondary metabolites than fast-growing plants. Could this have caused the differences observed by Barry?

McAllan: No, they were absolute effects. The lotus were harvested at maturity.

Pearce: They can be harvested at maturity and still have different rates of growth at a critical point in time.

Nordblom: I want to respond to the question of whether any varieties have been rejected on the grounds of residue quality. In Egypt, a traditional wheat variety is not being replaced by new, improved varieties because of lower quantity and quality of their crop residue. They were improved in terms of the breeders' objective of higher grain yield but rejected by farmers because of quality and quantity of crop residue.

Thomson: We have seen considerable contrast among the four papers presented during this session in the approach used, from the very animal-oriented approach we use at ICARDA to the much more detailed approach of Dr. Pearce, looking at individual components. At ICARDA we will continue the animal work and introduce the laboratory work. I feel it is important to have a solid animal input in this research. We should consider national programmes and universities in addition to international centres when discussing research methods. Animal evaluations are often more appropriate where complex and expensive materials are difficult to obtain.

Yilma: I think the search for better quality in crop residues will be possible for the plant breeder as long as it does not compromise agronomic and yield attributes. We have seen that there is variation among cultivars and crop species in straw quality and traits that determine straw quality such as morphology. We have to determine the difference between local cultivars and improved cultivars in quality of crop residue. We need more information on why farmers grow a particular cultivar and the importance they place on feeding crop residue. Can simple and specific criteria, either laboratory or animal, be established that can be incorporated into a breeding programme for looking at straw quality? Alternatively, can we describe an ideal ecotype in terms of morphological proportions, height, maturity, tillering etc? These are things that a plant breeder would ask.

Van Soest: A particular set of factors will be unique to each plant species. We need to determine the limiting factors in relationship to the desired nutritive value of the plant.

McDowell: It seems that the plant breeder is looking for a recommendation on phenotypic characteristics of the plant that can be selected to meet animal needs. On the other side, there are the laboratory techniques that indicate that this may be misleading. We need a close integration between the plant and animal scientist so that we can begin to develop an indexing system that could also include cost factors for evaluating crop varieties. Much more effort is required to develop these indices, including research on the effects of preservation and time of harvest. Dr. Pearce, have you looked at the effects of early harvest and artificial drying on preserving the solubles in residue fractions?

Pearce: We have thought of this but grain drying under our conditions is too expensive. Grain harvest and the length of the period between grain maturity and harvest is determined by weather conditions.

McDowell: Would you recommend picking up the straw the day after combine-harvesting and bailing it to reduce respiration and maintain higher levels of fructans?

Pearce: No, by the time the plant has obtained that low a moisture content it is dead and respiration is finished. But this is not the case for irrigated rice, which is still green and actively growing after harvest.

Ørskov: Reed made a good point, that we need to use different criteria for each objective. We have to consider yield of different parts of the plant and whether animals are allowed to feed selectively. The message to the plant breeder is that there is no golden answer that will apply to everything. We have to be flexible and think about why we are using the method.

Schildkamp: Crop residues are used primarily for maintaining animals. Animal nutritionists should not necessarily look for the highest nutritive value but rather stress that crop residues should not fall below a certain standard below which animals cannot use the material for maintenance.

SESSION 4

Perspectives and implications for crop improvement programmes

GENETIC SELECTION FOR IMPROVED NUTRITIONAL QUALITY OF RICE STRAW--A PLANT BREEDER'S VIEWPOINT

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INTRODUCTION

In South and Southeast Asia, the primary agricultural activity is crop production. Plant breeders are engaged in increasing crop productivity per unit area per unit time and in improving grain quality. Straw quantity and quality have been secondary considerations, except as they directly affect crop yield, such as in resistance to insects, diseases and lodging (Khush and Kumar, 1987). Plant breeders are becoming increasingly aware of the need for whole-plant utilisation, and hence of the need to improve the utility of crop residues (Rexen and Munck, 1984). Ruminant livestock in the rice-producing areas of Asia are dependent on rice straw for part of their nutrient requirements during the cropping seasons and in dry or drought periods (Doyle et al, 1986). But the biodegradability and voluntary intake of rice straw by ruminants are low. The feeding value of rice straw can be improved by treating it with alkali or urea, but genetic improvement of straw quality would be a cheaper and more logical approach. However, feed value should be improved without reducing grain yield and quality. Harvest straw (upper 40-50 cm below the panicle neck) is the most economical fraction of the rice crop residue, since it is already collected and partly dried in threshing areas. Stubble is either burned or ploughed under.

We discuss here collaborative research at IRRI examining the feasibility of improving the feed value of rice straw for ruminants.

METHODS

Dry-matter, crude-protein and organic-matter contents of the straw of various rice genotypes were determined using AOAC (1970) procedures. Neutral-detergent fibre (NDF), cellulose, lignin and silica contents were determined according to Goering and Van Soest (1970). *In vitro* organic-matter digestibility (IVOMD) was measured as described by Minson and McLeod (1972). The rumen fluid was taken from a fistulated buffalo fed a rice-straw-based diet supplemented with a concentrate mix containing 15% crude protein at 1.0% liveweight. Cellulase solubility (*in vitro* dry matter solubles, IVDMS) was estimated at the Tropical Development and Research Institute (TDRI), London, by the method of Goto and Minson (1977).

VARIATION IN COMPOSITION AND *IN VITRO* DIGESTIBILITY

Variations in chemical composition and *in vitro* digestibility of rice straw have been summarised by Juliano (1985) and Doyle et al (1986).

Varietal differences have been suggested by many researchers, but others have reported little or no variation. Rice straw contains less lignin but more silica and oxalic acid than other cereal straws (Van Soest, 1981; Juliano, 1985).

Various morphological, chemical and environmental factors affect the nutritional value of cereal straws (Doyle et al, 1987; Neilson and Stone, 1987; Nicholson, 1984; Pearce, 1986; Preston and Leng, 1987; Van Soest, 1982). These include cell-wall content; content of lignin and silica; ratio of leaf blade, leaf sheath and stem; length of harvest straw; soil fertility and added fertilizer level; soil moisture and degree of senescence of straw at harvest; growth duration; resistance to pests; and plant height.

Cell contents (neutral-detergent solubles) are more readily digestible than cell walls, measured as neutral-detergent fibre (NDF) (Van Soest, 1982). Lignin and silica are reported to reduce the digestibility of rice straw (Van Soest, 1981). However, manipulation of the silica content of three rice varieties by hydroponics did not substantially change the *in vitro* organic-matter digestibility of the total straw at harvest (Balasta et al, in press) (Table 1). Thus, lignin is probably the most important factor that limits digestibility of rice straw in ruminants (Neilson and Stone, 1987).

Harvest straw is made up of leaf blades, leaf sheaths, the stem and the panicle rachis. The proportions of these components are affected by straw length. In the Philippines, straw is cut 40-50 cm below the base of the panicle to facilitate holding during threshing. The stem contains less ash and protein but more cellulose than the

Table 1. Crude silica content and in vitro organic matter digestibility of harvest straw of IR rices grown hydroponically with different levels of silica.

Variety	Season	Property	SiO_2 concentration (ppm)					LSD
			0	100	200	300	400	(5%)
IR36	1985 WS	Crude silica (%)	0.7	7.4	8.8			1.3
		IVOMD (%)	52.0	47.8	50.7			ns
IR42	1985 WS	Crude silica (%)	0.7	4.0	8.4			1.3
		IVOMD (%)	57.4	50.0	50.1			4.6
IR58	1986 DS	Crude silica (%)	0.4	4.5	9.4	12.1	15.4	1.9
		IVOMD (%)	40.5	48.1	43.9	44.1	41.7	ns
IR36	1986 DS	Crude silica (%)	0.4	4.7	9.4	11.2	12.2	1.9
		IVOMD (%)	46.8	44.7	43.9	35.4	46.2	9.6

WS = wet season; DS = dry season.

Source: Balasta et al (in press).

leaves (Doyle et al, 1986). In Malaysian rices, mean IVOMD of the plant parts were blades 44%; sheaths 45%; and stem internodes 42%. IVOMD varied more in blades than internodes (Doyle et al, 1986). Roxas et al (in press) found that IVOMD of stem internodes tends to be higher than that of leaf blades and leaf sheaths, although the NDF content of the internodes was not necessarily lower (Table 2). Internodes have a higher cellulose content than leaves.

Table 2. Composition of leaf blade 2 (LB), leaf sheath 2 (LS), and internode 2 (I) of IR36 and IR42 rice plant at harvest, 1984 wet season.

Property (%)	IR36			IR42		
	LB	LS	I	LB	LS	I
IVOMD	40	45	51	34	37	50
NDF	67	72	62	70	70	71
Cellulose	30	37	44	31	35	41
Hemi-cellulose	13	11	11	16	10	11
Lignin	6.2	3.3	3.7	5.5	4.5	7.7

Source: Roxas et al (in press).

Stubble (basal residue after harvest) contains less crude protein and more cellulose than harvest straw (Hart and Wanapat, 1986; Winugroho, 1986). IVOMD was higher in stubble than harvest straw in rainfed lowland rice in northeast Thailand (Hart and Wanapat, 1986) and in Ciawi, Indoneasia (Winugroho, 1986), but lower in lowland rice at IRRI (Roxas et al, in press). In four lowland varieties at IRRI, IVOMD of harvest straw was higher than that of whole straw (45-50% vs 36-46%), suggesting that the IVOMD of stubble is lower than that of harvest straw (Roxas et al, in press). IVOMD of stubble increases when the stubble is left ungrazed (Hart and Wanapat, 1985), probably due to ratooning and continuing growth of unproductive tillers.

Current breeding efforts which aim at incorporating resistance to insects, diseases and lodging also lead to improvements in harvest straw quality by reducing straw damage. Duration of growth and nitrogen fertilizer levels also affect protein content of the straw. Early-maturing modern rices have higher grain and, possibly, higher straw protein contents than medium-maturing varieties (IRRI, 1985), and tend to have thinner straw and be more susceptible to lodging than medium-maturing rices (IRRI, 1984). Nutrient supply affects the ash content of straw. Soil N level affects protein content.

The *brittle stem* mutants of rice variety Balilla 28 have been reported to have higher lignin and hemicellulose and lower alpha-cellulose contents in the stem than the parent (Sharma et al, 1986). However, the IVOMD of their harvest straw (32-49%) overlapped with that of the Balilla 28 parent (36%) (Juliano et al, in press).

Semi-dwarf rices were shown to have similar if not greater harvest straw IVOMD than tall varieties such as H4 (Roxas et al, 1985) (Table 3). Selected strong- and weak-stemmed traditional and semi-dwarf varieties showed similar harvest straw IVOMD despite differences in straw length and blade:sheath:stem ratio (Juliano et al, in

Table 3. IVOMD of IR36, IR42 and IR58 harvest straw.

Year	Season	Type of plot[1]	Harvest straw IVOMD (% of total) IR36	IR42	IR58	H4	Source
1982	DS	D	38	41	-	-	a
1982	WS	A/DP	53	47	-	45	b
1983	DS	A/DP	51	41	-	39	b
1984	WS	PB	50	50	45	47	c
1985	WS	D	45	41	42	-	d
1986	DS	D	33	36	34	-	d
1986	DS	M	52	-	49	-	e

1. D=demonstration plot; A/DP=agronomy/date of planting trial; PB=plant breeding plot; M=multiplication plot.

Sources: a. Roxas et al (1984); b. Roxas et al (1985); c. Roxas et al (in press); d. Juliano et al (in press); e. IAS/UPLB-IRRI, unpublished data (see Table 6).

press) (Table 4). In addition, the quantity of harvest straw from traditional and modern varieties harvested traditionally and threshed for the same grain yield is similar. Only the quantity of stubble is higher in traditional varieties.

Recent studies by Roxas et al (1985) suggest that varieties differ in harvest straw IVOMD. In two seasons, IR36 had consistently higher IVOMD than its sister variety IR42 (Table 3). In other IRRI trials, relative IVOMD values for these two varieties were different from another early-

Table 4. Properties of harvest straw of strong and weak stemmed IR and traditional rice varieties, 1986 dry season.

Property	IR rices		Traditional rices	
	Non-lodging[1]	Lodging[2]	Strong stem[3]	Weak stem[4]
IVOMD (%)	33	34	36	34
NDF (%)	69	70	67	68
Crude ash (%)	20	22	21	21
Weight (% of total straw)	76	78	47	39
Blades:	41	36	52	48
Sheaths:	43	37	30	29
Stem ratio	16	27	18	23
Growth duration (d)	132	116	123	127

1. IR8 and IR42.
2. IR36 and IR40.
3. Century Patna 231-SLO 17, Khao Dawk Mali 105, and Gam Pai.
4. Tetep, TKM 6, and Binato.

Source: Juliano et al (in press).

maturing variety, IR58 (Roxas et al, 1984; in press; Juliano et al, in press). Differences in IVOMD were not related to differences in NDF, cellulose, lignin and silica contents of the straw.

A survey of harvest straw of 29 IR varieties and IR28150-84-3 in two crop seasons (dry and wet) revealed differences in IVOMD among the semi-dwarf rices. However, sample ranking was not strictly maintained in the two seasons (Juliano et al, in press) (Table 5). IVOMD of IR36 harvest straw was higher than that of IR42 and IR58 harvest straw in the 1985 wet season but lower than that of IR42 straw in the 1986 dry season (Table 3). In both seasons IVOMD correlated negatively with crude ash; the correlation with straw N was positive in the first crop and negative in the second crop (Table 5). IVOMD and NDF showed a non-significant negative correlation. The correlation between seasons in IVOMD and content of NDF were not significant, suggesting large environmental influence on the chemical and nutritive properties of harvest straw.

Using the pepsin-cellulase method, IVDMS of harvest straw of 22 IR rice varieties was found to range from 23.3 to 30.7% in the 1985 wet season crop and from 20.8 to 27.5% in the 1986 dry season (Bainton et al, 1987b; TDRI, unpublished data). Harvest straw IVDMS of the two crops were not significantly correlated (R=0.32). IVDMS was not significantly correlated with plant height or proportion of blade, stem and sheath in the harvest straw, but was higher in stems than blades and sheaths. Similar ranges of variation have been reported among IR36 straw samples at IRRI and among nine varieties in two crops of the International Rice Yield Nursery (Bainton et al, 1987a).

To estimate the relative contribution of variety and environment to variation in IVOMD of harvest straw, a cooperative experiment is underway for the 1987 wet season and 1988 dry season at IRRI using five tall and five semi-dwarf rices at 0 and 90 kg N ha^{-1} (applied basal). The harvest straw will be analysed jointly by TDRI, UPLB and IRRI scientists.

Table 5. Properties of 29 IR varieties and IR28150-84-3 plants at harvest 1985 wet season (WS) and 1986 dry season (DS) and their correlation[1] with in vitro organic matter digestibility.

Property	Range		Correlation coefficient with IVOMD		Correlation between seasons
	1985 WS	1986 DS	1985 WS	1986 DS	
Growth duration (days)	102-142	103-138	-0.01	-0.54**	0.97**
Harvest index	0.28-0.60	0.29-0.64	-0.28	-0.69**	0.54**
N harvest index	0.38-0.71	0.40-0.74	-0.36	-0.66**	0.32
N content of straw (% w.b.)	0.56-0.97	0.52-0.90	0.46**	-0.43*	0.47**
N content of panicle (% w.b.)	1.03-1.50	0.94-1.41	0.19	-0.51**	0.30
Harvest straw (% of total)	38-64	46-74	-0.25**	0.38*	0.73**
IVDMD (%)	34-47	33-44	0.88	0.76**	0.01
IVOMD (%)	34-49	27-42	-	-	0.22
Crude ash (% d.b.)	18-23	18-26	-0.38*	-0.65**	0.49**
NDF (% d.b.)	66-76	68-74	0.25	-0.11	0.13

Source: Juliano et al (in press).

Significant r = 0.361 at the 5% level and 0.463 at the 1% level (n=30).

FEEDING STUDIES

In addition to the environment-variety interaction on the chemical composition and IVOMD of rice straw, the correspondence of IVOMD to feed value (voluntary intake and *in vivo* digestibility) needs to be verified. Rice stubble with higher IVOMD than harvest straw (35 vs 25%) showed lower intake and digestibility when fed with concentrates to sheep and goats (Winugroho, 1986). However, among five Thai rainfed lowland rice varieties with similar IVOMD (45-51%), one variety showed higher organic-matter digestibilities in sheep than the others, although voluntary intakes were similar (Cheva-Isarakul and Cheva-Isarakul, 1985a; 1985b).

IR 36 and IR58 were multiplied at the IRRI Experimental Farm in the 1986 dry season to produce enough harvest straw and stubble for feeding trials with growing cattle. IVOMD was similar in IR36 harvest straw and stubble and IR58 harvest straw (Table 6). Voluntary intake and digestibility of the three samples were also similar (Table 6). Initially, intake of IR58 harvest straw was less than that of IR36 straw but after a week of feeding intakes were similar. We need to determine the minimum difference in IVOMD that would be reflected in a significant difference in *in vivo* digestibility in ruminants.

GENETIC SELECTION FOR NUTRITIONAL QUALITY OF STRAW

The results presented show that chemical composition and digestibility of straw varies among rice varieties. This variability presumably could be exploited to improve the nutritional value of the straw of future varieties. However, rice is grown primarily for grain and, at present, no attention

Table 6. Chemical and nutritional properties of IR36 and IR58 harvest straw and IR36 stubble fed to cattle, 1986 dry season.

Property (% dry basis)	Harvest straw IT58	Harvest straw IR36	IR36 stubble
Crude ash	21.7	22.4	26.2
Neutral-detergent fibre	63.4	66.0	64.8
Acid-detergent fibre	54.9	55.6	58.8
Hemicellulose	8.5	10.4	6.1
Cellulose	35.9	35.7	35.0
Lignin	4.6	4.8	5.5
Crude silica	14.4	15.1	18.2
IVDMD (% of total)	46.2	48.6	44.3
IVOMD (% of total)	49.0	51.8	50.2
Voluntary intake[1] (% of body wt d^{-1})	1.6	1.9	1.9
In vivo dry-matter digestibility[1] (%)	39.0	43.0	45.0

1. Measured on growing cattle fed with rice straw/stubble and supplemented with concentrated mix at 1% of body weight.

Differences among means were not significant.
Source: IAS/UPLB-IRRI (unpublished data).

is paid to the nutritional quality of the straw. With the present emphasis on increasing grain yield it is unlikely that any institution will undertake a selection programme to improve the nutritional value of straw but plant breeders may be persuaded to evaluate their advanced breeding lines for the nutritional value of the straw. Other traits being equal, plant breeders could then select lines with better nutritional quality of straw. However, availability of simple screening techniques for evaluating the straw quality of breeding materials is a prerequisite.

SUMMARY

The wide variation in the ratio of leaf blade:leaf sheath:stem, chemical composition and IVOMD of harvest straw suggests that varietal differences in straw nutritional quality exist. However, environmental factors significantly affect IVOMD. Only after the environmental influence on IVOMD is understood and minimised can effective IVOMD screening be justified in a rice breeding programme. The screening method chosen should correlate with *in vivo* nutritional value of harvest straw. When selecting for straw quality, we must at the same time maintain or even improve grain yields and grain quality, the major goals of current rice breeding programmes.

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DISCUSSION

Van Soest: What are the problems connected with low silica levels in the nutrient solutions on which rice plants were grown?

Khush: Generally low yields.

Mueller-Harvey: Are phenolic compounds of any significance in rice breeding?

Khush: Yes, in relation to insect resistance.

Ørskov: Are there no relationships between grain yield and straw quality?

Khush: No clear relationship has been found. Although plant breeders must concentrate on improving grain yields in rice, it is possible that straw quality can be given some attention.

Little: Do higher-yielding rice varieties have higher crude protein contents in their straw?

Capper: Traditional varieties may have about 4% crude protein, rising to 6 or 7% in improved varieties. From the research on rice to date it appears that selection for grain yield has not reduced straw quality. However, one problem in investigating rice straw quality is the variability both within and between plots and there seems to be no satisfactory explanation for this.

Little: It appears that there is only little genetically determined variation in the nitrogen content of straws. Will it be possible to select for this?

Khush: The direction breeding programmes take will depend upon priorities and the relative importance of grain and straw.

Thomson: At ICARDA the facilities devoted to examination of straw quality are modest and take up only a small proportion of the budget. I consider that it is not beyond the resources of the CG centres to address the question of straw quality.

EVALUATING SORGHUM CULTIVARS FOR GRAIN AND STRAW YIELD

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INTRODUCTION

Cereal lines in breeding trials are usually evaluated on mean grain yield, although attention is sometimes given to yield stability or grain quality. Mean yield is most relevant where there is only one product of interest, such as grain, but may be misleading where there are joint products, especially if uses of the products differ. One such example is sorghum.

This paper proposes a method to estimate the trade-off between sorghum grain and straw yield in agronomic trials. First, a theory of the conflict between the two products is described. Second, data from sorghum cultivar trials in Ethiopia are presented. Third, a method of valuing sorghum grain and straw is given. Lastly, conclusions about breeding strategies are drawn.

JOINT PRODUCTS AND PRODUCTION EFFICIENCY

The conflict between grain and straw yield can be modeled with the theory of joint products (Henderson and Quandt, 1971). Consider a sorghum cultivar producing both grain and straw from a single input, land, as illustrated in Figure 1. The curve in Figure 1 is commonly known as a transformation curve of two outputs as function of one input.

The relation describing the outputs of the two products is expressed as an implicit function of land input:

$$l = f(g,s)$$

where s is straw, g is grain, and l is land.

By taking the total differential of this function and setting it equal to zero, one can solve for the ratio of the derivatives with respect to land input--[(ds/dl)/(dg/dl)]--the rate at which one product is sacrificed to produce the other at a given level of land input. The negative of the ratio of the derivatives is defined as the rate of product transformation.

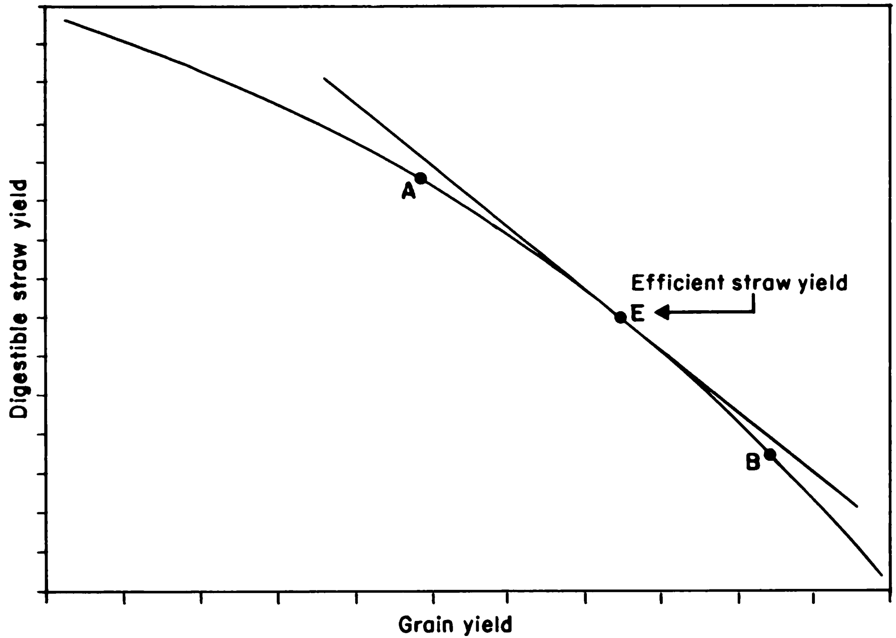
The choice of the point at which to operate along a transformation curve is determined by the prices of the outputs, p(g) and p(s), where 'p' represents market price. Assuming that market prices are fixed, the optimal production point on a transformation curve is that where

$$[p(g)/p(s)] = [(ds/dl)/(dg/dl)]$$

that is, where the ratio of grain price to straw price is equal to the rate of product transformation of straw into grain. The ratio of grain price to straw price is the tangent in Figure 1.

Two types of efficiency can be analysed with Figure 1. Technical efficiency means producing the maximum amount of either product for a given

Figure 1. *Transformation curve, grain and digestible straw.*



amount of the other product; that is, a producer who is technically efficient operates at some point on the transformation curve. Allocative efficiency means producing the two products in the right proportions, where those proportions are dictated by the price ratios of the products. A producer who is allocatively and technically efficient operates at the optimal point on the transformation curve. Graphically, the optimal point is that at which the price ratio is tangent to the transformation curve, shown by point E in Figure 1. It is possible to be allocatively efficient and technically inefficient, and vice versa.

EVALUATING GRAIN AND STRAW

Data from sorghum trials conducted by the Ethiopian Institute of Agricultural Research and ILCA were used to test the theory outlined above. Table 1 shows descriptive statistics for grain yield, straw yield and digestibility for sorghums tested at Debre Zeit in 1984 and at Debre Zeit and Nazareth in 1985 (IAR, 1986). Debre Zeit is at 1850 metres above sea level, in the transition zone between the highlands and lowlands of Ethiopia. Nazareth is at 1500 m and has a hotter, drier climate.

The sorghum cultivars were evaluated in the field in the usual way. Straw samples of each cultivar were analysed in the laboratory for digestibility (Reed et al, 1987). In 1984, digestibility was estimated for leaves and stems and in 1985 for leaf blades, leaf sheaths and stems. The digestibilities in Table 1 are weighted averages of whole plant digestibility, where the weights are the fractions of each plant

Table 1. Descriptive statistics for three sorghum trials.

	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Apparent digestibility (%)
Debre Zeit, 1984			
Brown sorghums	2.61	5.38	53.6
Red sorghums	2.50	5.97	51.4
White sorghums	2.54	5.18	51.5
Overall	2.55	5.51	52.2
Debre Zeit, 1985			
Brown sorghums	4.46	8.37	52.3
Red sorghums	5.72	7.11	55.5
White sorghums	2.94	6.49	54.0
Overall	4.58	8.13	52.8
Nazareth, 1985			
Brown sorghums	4.18	5.13	57.3
Red sorghums	3.68	4.93	60.1
White sorghums	0.92	2.80	57.0
Overall	4.00	5.02	57.7

part in the oven-dried straw dry matter (DM) of the plant samples[1].

1. A more complicated case occurs when straw is fed for an extended period. If straw quality degrades, then its quantity over the feeding period must be adjusted. However, only if there were different rates of decay for different cultivars, would decay affect the comparisons among cultivars.

The value of grain for sale is the market price. Market prices for sorghum grain are given in Table 2 for the area around Debre Zeit. There are three possible values of sorghum straw. The first is its market price. The second is its value in maintaining a herd if it is the only feed. In this case, the value of sorghum straw is the value of annual production from the herd, at market prices, divided by the quantity of straw necessary to maintain the herd. This is called

Table 2. Unit values of sorghum grain and straw.

	Average (Oct 1984-Sept 1985)	Oct-Jan	March-April	July-Sept
Grain price (EB kg^{-1})[1]	0.53	0.50	0.50	0.60
Straw price (EB kg^{-1})	0.23	0.20	0.20	0.30
Average straw digestibility (%)[2]	54.3			
Sorghum digestibility as % of teff digestibility	80.0			
Digestible straw price (EB kg^{-1})[3]	0.34	0.29	0.29	0.44
Grain/straw price ratios				
Average market value	1.50	1.70	1.70	1.36
Average maintenance value	3.50	3.43	3.13	3.94
Average supplementation value	1.23	1.30	0.98	1.42
Meat price (EB kg^{-1} LW)	1.97	1.90	2.00	2.00
Milk price (EB kg^{-1})	0.57	0.50	0.66	0.55
Manure price (EB kg^{-1})	0.05	0.05	0.05	0.05

1. EB = Ethiopian Birr. 1 US $ = 2.07 Ethiopian Birr.
2. The average sorghum straw digestibility is the mean of the three trials.
3. Digestible sorghum straw price is estimated by multiplying the teff straw price by the sorghum digestibility as a percentage of teff digestibility.

the average maintenance value in Table 2. The third is its value as a supplemental feed. In this case, assume that maintenance feeding requirements are satisfied from pastures and crop residues and that sorghum straw is used as a supplement for milk production. An energy balance model of milk production can then be used to calculate the value of the straw (Sandford, 1978). This is called the average supplementation value in Table 2. (Details of the calculations of the maintenance and supplementation values of sorghum straw are given in Appendix 1).

Table 2 gives illustrative values of sorghum grain/straw price ratios using the three methods. The highest grain/straw value ratio--that which places the lowest value on straw--is the maintenance value. The lowest ratio--that which places the highest value on straw--is the supplementation value.

The value of a cultivar is expressed in equations (1) and (2).

$$(1)\ V(g) = p(g)*q(g)$$

$$(2)\ V(s) = p(s)*q(s)$$

where V=value per hectare, p=price per kg, g=grain, q=quantity in kg per hectare, and s=straw. The quantity of animal production for a given straw consumption is given in equation (3).

$$(3)\ q(a) = f(q(s))$$

where q(a) is a quantity of animal product. Equation 3 can be understood as a very general representation of any of the three methods of calculating the productivity of straw.

The total value of a cultivar is

(4) V(t) = V(s) + V(g)

where V(s) and V(g) are estimated from equations (1) and (2), and t=total. Table 3 gives typical values for the total values of cultivars in the three trials[2].

THE CONFLICT BETWEEN GRAIN AND STRAW YIELD

The transformation curve in Figure 1 illustrates the conflict between grain and straw yield. To estimate the curve, the mean of each cultivar's grain and digestible straw DM yield was calculated across replicates at each site. Then, assuming

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2. Assumptions are that seed rates do not differ significantly between cultivars, so that net grain output per hectare is a linear transformation of gross output. All grain is sold and evaluated at market prices. Grain value would be affected if some is retained for home consumption. However, the results would be affected only if the fraction retained differed significantly between cultivars. Third, it is assumed that there are no market price differences between sorghum grain qualities, as shown by grain colour. Such differences would have an effect on the inter-cultivar comparisons. Fourth, no mixed straw sale/ straw feeding strategies are allowed. All straw is assumed to be sold, or to be fed for one purpose. Mixed strategies would only affect the comparison between cultivars if the proportions sold and fed differed between cultivars.

Table 3. Total values of cultivars (grain and digestible straw).

Debre Zeit, 1984					Debre Zeit, 1985					Nazareth, 1985				
		Straw use					Straw use					Straw use		
Cultivar	Grain colour	Market	Maint-enance	Supple-mentation	Cultivar	Grain colour	Market	Maint-enance	Supple-mentation	Cultivar	Grain colour	Market	Maint-enance	Supple-mentation
		--------	EB ha^{-1}	--------			--------	EB ha^{-1}	--------			--------	EB ha^{-1}	--------
1	R	1768	988	2099	1	B	4069	3020	4513	1	B	3296	2337	3703
2	R	2348	1548	2687	2	B	3102	2110	3523	2	B	2888	2117	3215
3	R	2416	1656	2738	3	B	4316	3173	4801	3	B	3029	2425	3285
4	W	2060	1203	2424	4	B	3704	2548	4195	4	B	4379	3388	4800
5	R	2618	1674	3019	5	B	4^99	3230	4738	5	B	2251	1803	2441
6	R	2747	1854	3125	6	B	3466	2331	3948	6	B	2624	2080	2855
7	R	2435	1570	2802	7	B	3885	2673	4399	7	B	2283	1715	2524
8	R	2276	1449	2627	8	B	3427	2233	3933	8	B	2279	1824	2472
9	B	2575	1488	3037	9	B	3380	2028	3953	9	B	2371	1754	2633
10	B	2627	1691	3024	10	B	3087	2331	3408	10	B	3416	2744	3701
11	B	2320	1391	2714	11	B	3659	2223	4268	11	B	3641	2717	4033
12	B	2444	1710	2755	12	B	3448	1581	4240	12	B	3071	2086	3488
13	W	2292	1483	2635	13	B	2821	1826	3243	13	B	2179	1791	2344
14	W	2567	1667	2949	14	B	3547	2066	4175	14	B	3860	2907	4265
15	W	2358	1690	2642	31	R	5013	3872	5497	31	R	3686	2776	4071
16	B	1865	1404	2060	32	R	4319	3246	4774	32	R	2450	1698	2769
17	B	2806	1928	3178	33	B	4222	3163	4671	33	B	4162	3267	4541
18	R	2448	1768	2736	34	R	4626	3344	5169	34	R	3456	2436	3889
19	W	1837	1272	2077	35	B	5141	3671	5765	35	B	4970	3068	5776
20	B	2049	1238	2392	36	B	4260	3136	4737	36	B	3868	2915	4273
21	B	2454	2029	2634	37	B	4182	3571	4441	37	B	2771	2303	2969
22	Y	1976	1399	2221	38	B	5119	3723	5711	38	B	4729	3514	5244
23	W	2854	2091	3178	39	R	3684	2926	4006	39	R	2338	1826	2556
24	W	2225	1638	2474	40	W	2772	1833	3170	40	W	1036	608	1217
Mean		2348	1576	2676			3897	2744	4387			3126	2337	3461
s.d.		307	269	347			691	692	722			954	690	1079

Total values are calculated using the average grain price and the grain/straw price ratios from Table 2.

that straw yield was zero if grain yield was zero, the Pythagorean theorem was used to calculate the maximum distance from the origin at each site by finding the maximum of the sum of the squares of grain and straw DDM yield for each cultivar, denoted by:

$$\max(\text{grain}_i{}^2 + \text{straw DDM}_i{}^2)$$

where 'i' is the cultivar index. This maximum distance was the most efficient combination of grain and straw production for cultivars at a site.

Using that maximum distance, the efficient straw yield (S_i) corresponding to every grain yield was calculated by

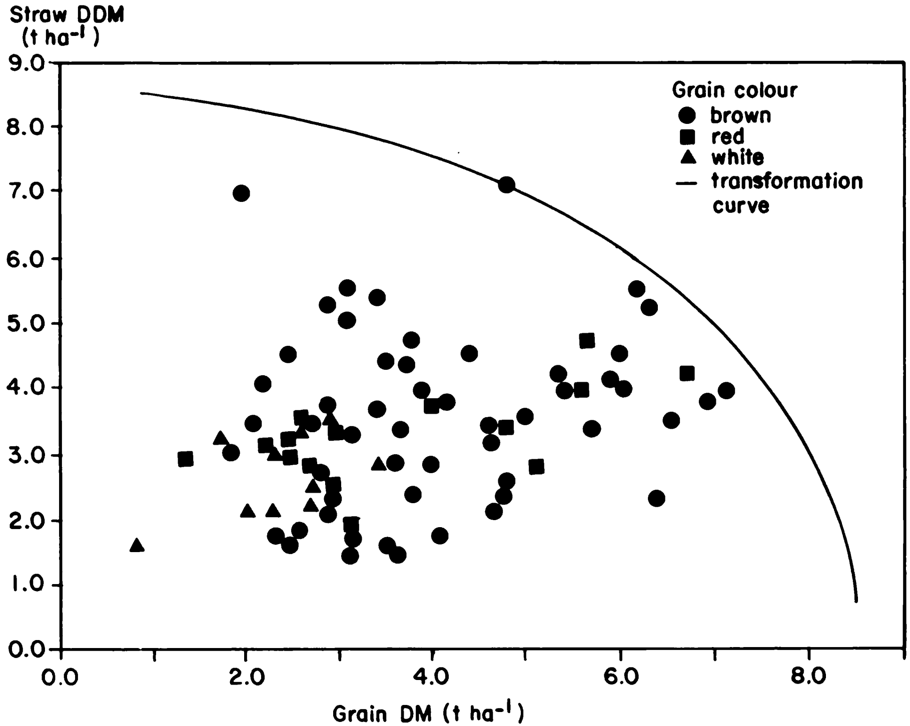
$$(\hat{S}_i) = [\max(\text{grain}^2 + \text{straw DDM}^2) - \text{grain}_i{}^2]^{1/2}$$

Plotting the efficient straw yield against actual grain yield gave the transformation curve in Figure 2 for pooled data from the three trials.

The slopes of the transformation curves, which are interpreted as the losses in digestible straw yield with an increment in grain yield, are shown below. They were estimated for each trial by regressing the efficient straw yields on actual grain yield and on actual grain yield squared.

	Grain yields	
	Mean	Maximum
Debre Zeit, 1984	-0.69	-1.10
Debre Zeit, 1985	-0.72	-1.33
Nazareth, 1985	-0.55	-0.88

Figure 2. *Transformation curve, grain and digestible straw, pooled trials.*



For example, at Debre Zeit in 1984, at the mean grain yield of 2.55 t ha^{-1}, a 1 kg increase in grain yield would have reduced sorghum straw DM yield by 0.69 kg; at the maximum grain yield of 3.58 t ha^{-1}, a 1 kg increase in grain yield would have reduced sorghum straw DM yield by 1.10 kg.

CHOOSING EFFICIENT CULTIVARS

Transformation curves can be used to choose cultivars that are technically and allocatively efficient. Technical inefficiency is measured by the value of the straw yield lost by not producing on the transformation curve for a given grain yield; it is equal to efficient straw yield minus actual straw yield times straw price, i.e.

$$(\hat{S}_i - s_i)*p(s).$$

In terms of Figure 1, an increase in allocative efficiency, represented by the movement from point A to point E on the curve, raises grain yield and reduces straw yield. A movement from point B to point E reduces grain yield and raises straw yield. Both movements are increases in allocative efficiency.

The slopes of the estimated transformation curves at the mean grain yields were between -0.55 and -0.72. The absolute values of those ratios are smaller than the grain/straw price ratios, implying that an allocatively efficient cultivar would have a higher grain yield and a lower straw yield than any tested in these trials. Therefore, allocative inefficiency is measured against the standard of the cultivar having the highest grain/straw ratio, not against the allocatively efficient price ratio. Allocative inefficiency is equal to the value of the grain yield lost (gained) in moving along the transformation curve minus the value of the straw yield gained (lost).

Table 4 shows the costs of technical and allocative inefficiency in sorghum cultivars in the three trials. Technical inefficiency--producing too little straw at a given grain yield--is the major cost of inefficiency in these trials.

In practice, only cultivars with high grain yields are usually included in extension programmes. Such programmes concentrate on one part of the grain yield distribution and neglect the overall value of the plant. What are the consequences for farm income if only cultivars with higher grain yields are selected for extension?

Cultivars were ranked by grain yield, by the total revenue at market prices from grain and digestible straw production, by technical efficiency, and by allocative efficiency (Table 4). These criteria were chosen because grain yield is probably the extension criterion; the value of production is the overall return to the cultivar; technical inefficiency is a measure of the return to raising straw yield while holding grain yield constant; allocative inefficiency is a measure of the return to reallocating dry-matter production in line with the prices of grain and straw.

Spearman rank correlations were as follows:

	Grain yield	Technical efficiency
Revenue	0.878**	
Technical efficiency	-0.164	
Allocative efficiency	0.313**	0.654**

** Significant at P<0.01

Table 4. Costs of inefficiency in sorghum cultivars.

Debre Zeit, 1984					Debre Zeit, 1985					Nazareth, 1985				
			Inefficiencies ($EB\ ha^{-1}$)					Inefficiencies ($EB\ ha^{-1}$)					Inefficiencies ($EB\ ha^{-1}$)	
Cultivar	Grain yield ($t\ ha^{-1}$)	Total value (EB/ha)	Tech-nical	Alloca-tive	Cultivar	Grain yield ($t\ ha^{-1}$)	Total value (EB/ha)	Tech-nical	Alloca-tive	Cultivar	Grain yield ($t\ ha^{-1}$)	Total value (EB/ha)	Tech-nical	Alloca-tive
1	1.44	1769	509	641	1	5.11	4074	770	399	1	3.88	3298	1382	616
2	2.48	2349	315	255	2	3.43	3104	1290	849	2	3.56	2889	1678	730
3	2.71	2417	314	188	3	5.35	4321	542	380	3	4.23	3031	1768	498
4	1.81	2062	364	494	4	4.17	3705	851	687	4	5.83	4374	878	44
5	2.64	2620	93	207	5	5.50	4289	593	361	5	3.14	2252	2145	899
6	3.01	2748	63	109	6	3.78	3471	1025	748	6	3.62	2617	1934	745
7	2.49	2436	230	253	7	4.38	3887	834	523	7	2.92	2284	2029	983
8	2.28	2277	322	321	8	3.56	3429	1012	802	8	3.18	2280	2139	877
9	2.22	2577	0	342	9	3.09	3382	881	980	9	2.96	2372	1960	964
10	2.68	2628	96	196	10	3.97	3088	1500	656	10	4.79	3417	1567	312
11	2.12	2321	221	377	11	3.41	3661	725	857	11	4.61	3642	1286	368
12	2.82	2445	318	156	12	1.98	3451	345	1448	12	3.40	3072	1430	794
13	2.36	2293	330	296	13	2.90	2823	1364	1057	13	3.15	2180	2229	888
14	2.65	2569	147	203	14	3.10	3549	714	979	14	4.95	3862	1169	265
15	2.82	2360	403	157	31	6.66	5015	187	41	31	4.73	3687	1277	332
16	2.39	1865	770	285	32	5.52	4321	712	210	32	2.79	2451	1809	1036
17	3.15	2807	36	76	33	5.37	4223	776	244	33	5.66	4163	1051	82
18	2.96	2449	350	121	34	5.60	4628	422	194	34	4.03	3458	1278	560
19	2.09	1838	693	389	35	6.11	5144	0	100	35	4.75	4973	0	323
20	1.90	2050	410	460	36	5.29	4262	717	264	36	4.96	3870	1165	262
21	3.58	2455	460	5	37	6.37	4183	995	65	37	4.07	2771	1979	546
22	2.32	1977	634	308	38	6.25	5121	42	81	38	5.95	4731	547	18
23	3.52	2855	52	12	39	5.09	3685	1242	316	39	3.15	2339	2069	888
24	2.76	2226	521	172	40	2.94	2773	1430	1040	40	0.92	1036	2369	1891
Mean	2.55	2350	319	251		4.54	3899	790	553		3.97	3127	1547	622
s.d.	0.52	308	216	155		1.33	691	419	397		1.18	954	588	425

Total value is calculated using the average digestible sorghum straw price and the average grain price from Table 2.

Selecting cultivars for grain yield would, in effect, select for revenue and for allocative efficiency. However, it would tend to select cultivars that are technically inefficient, in that they produce too little straw for their grain yields.

CONCLUSIONS

In Ethiopia, grain/straw price ratios are so high that continued emphasis on grain yield at the expense of straw is justified. The estimated trade-off between grain and straw yield is small enough that much higher grain yields would have to be achieved before that trade-off began to reduce total revenue from sorghum production. However, one study from central India (Walker, 1987) shows lower grain/straw price ratios, which would favour cultivars with higher straw/grain product ratios.

There was a significant ($P<0.01$) positive correlation between cultivar rank on grain yield and rank on revenue. With few exceptions, those cultivars having the highest grain yields would not suffer a straw yield penalty large enough to make them inferior to low grain yielders, which gave more straw. This suggests that extension programmes could, like breeding programmes, safely insist on grain yield, if the market prices of grain and straw reflect their values to the farmer.

If the choice is among sorghum cultivars to include in a screening programme, these data imply that straw yield would probably not be relevant. Of the 10 cultivars yielding more than 5.5 t of grain DM ha^{-1}, eight ranked among the top 10 on revenue and four ranked among the top 10 on straw yield. The trade-off between grain and straw yield would not dramatically affect decisions about including cultivars in a screening programme. Furthermore, the low revenue ranks of some cultivars might simply reflect selection for high grain/straw ratio, and not a necessary physical trade-off between grain and straw yield.

The situation might be different in an extension programme. Where the choice is among cultivars to extend to farmers in different environments and with different preferences, the decisions to extend a cultivar with high grain yield (e.g. #21 in 1984, highest grain yield and second lowest straw yield) would have to be chosen carefully because of the obvious possibility that its low straw yield would impair its adoption where the grain/straw price ratio is lower than that used in this paper. To take the converse case, it is unlikely that a high straw/low grain cultivar would be adopted simply because of its superior straw yield.

Many cultivars are technically inefficient, in that they produce much less straw, at given grain yields, than do the more efficient cultivars tested. Major gains could be made by raising straw yields to efficient levels while preserving grain yields.

The general advantage of grain over straw would be changed if sorghum straw is a supplement to a maintenance regime of pastures. In that case, the grain/straw price ratio falls and it becomes more profitable to select sorghum cultivars with lower grain/straw ratios. However, it is unlikely that peasant farmers have sufficient pastures for maintenance: they are thus obliged to use crop residues for low productivity maintenance as well as for higher productivity supplementation.

The apparent differences in straw yield, straw digestibility, leaf and stem digestibility and leaf/stem ratios across cultivars (and, in the case of stem dry matter, across grain colour groups) need to be investigated systematically. It is possible that overall digestible straw yield is not the most relevant criterion to use in considering straw yield in such trials. It may be that some cultivars with high leaf/stem ratios could be exploited to provide highly digestible feed at key times in the cropping season when other sources of feed are scarce.

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APPENDIX 1. STRAW VALUE CALCULATIONS.

Herd structure	No.	End of year LW (kg)	LW per class (kg)	Off-take[1] (kg LW)
Breeding cows	1.0	250	250	20
Calves	1.0	100	100	8
Heifers	1.0	167	167	13
Males	2.0	312	625	50
Total	5.0		1142	91

1. Assumed offtake rate of 8.0% for all classes.

Animal productivity parameters

Annual LW in herd (kg)	1142
Calving rate (%)	50.0
Milk production per lactating cow per year (kg)	400
Base intake of digestible dry matter (DDM) (% LW per day)	2.5
Annual DDM intake per herd (kg)	10 418
Percentage of intake converted into manure	20.0

Maintenance model, assuming all intake is from crop residues

Annual LW offtake (kg)	91
Annual milk production (kg)	200
Annual manure production (kg)	2084
Value of draught oxen for grain production (Birr)	384
Annual value of production from herd (Birr)	782
Average straw value (Birr kg^{-1} DDM)	0.08

Supplementation model, assuming maintenance is from pastures

Potential milk yield ($kg\ cow^{-1}\ yr^{-1}$)	1200
Intake of DDM per cow per year for maintenance (kg)	2281
Intake of DDM per cow per year for growth	
Assumed extra daily intake (% of base intake)	33.0
Intake of DDM growth ($kg\ cow^{-1}\ yr^{-1}$)	3034
Average straw value (Birr kg^{-1} DDM) (from energy budget)	0.46

Energy budget for cows in milk

Feed intake (kg DDM day^{-1})	8.31
Energy content of sorghum straw (kcal)	4000
Energy intake (kcal)	33 250
DM (% fresh feed weight)	50.0
Sorghum straw digestibility (%)	54.3
Metabolisable energy (ME) as percent of net energy (NE)	87.5
ME converted to NE in milk (%)	70.0
NE of milk (kcal $litre^{-1}$)	830
Average annual milk price (Birr $litre^{-1}$)	0.57
Energy value of straw (kcal kg^{-1} DDM)	666
Milk production (litre kg^{-1} feed)	0.80
Average straw value (Birr kg^{-1} DDM)	0.46

DISCUSSION

Witcombe: Can you explain exactly how the parameters grain and digestible straw yield relate to your terms technical and allocative efficiency?

McIntire: The terms are products of the first two parameters

Nordblom: Your analysis appears to ignore the differentiation of plant parts in terms of nutritive value.

McIntire: The digestible straw yield is, in effect, the weighted average of the fractions. There is, however, much more to be gained from exploiting differences in straw yield than differences in digestibility.

Witcombe: How do you make the final decision to select amongst the varieties that are similar in grain yield?

McIntire: The final choice depends upon prices.

Jenkins: The prices may vary considerably between seasons. How do you take this into account in your analysis?

McIntire: One can use long-term price expectancy figures.

McDowell: You have not included the benefit of preserving capital as live animals in your estimate of the value of straw for maintenance.

McIntire: Market prices are generally higher than the maintenance value, so this aspect is not important.

McDowell: Maintenance implies a minimum value for straw digestibility so that your parameter of digestible straw yield is not meaningful.

Berhan: There are other uses for sorghum stalks, such as house construction, which should be considered in the model.

McIntire: These are included in the market price.

Nordblom: This is only true if there is no market failure.

Reed: In parts of India the supplementation value is considerable and prices may be higher than you suggest.

SESSION 4

PERSPECTIVES AND IMPLICATIONS FOR CROP IMPROVEMENT PROGRAMMES

General discussion

Ørskov: We have not so far considered alternative uses of straw for industrial purposes.

Van Soest: The hemicellulose fraction which can be utilised by ruminants is of no value for paper making.

Reed: There are many issues relating to variation in straw quality which remain unresolved. This requires co-operation between animal nutritionists and plant breeders in research programmes to resolve the problems.

Jenkins: It is unlikely that any efforts will be made to breed for straw quality in Western Europe.

Goe: For developing countries we should start examining how farmers value their crop residues and how they utilise them.

Witcombe: ICRISAT has conducted such investigations with millet in India and found that farmers knew which varieties yielded more stover. As a consequence it is necessary to screen for crop residue yield and quality. In the ICRISAT millet breeding programme we are selecting for high fodder yield.

Fussell: It appears that the introduction of new sorghum and millet varieties in West Africa has resulted in a reduction in biomass per hectare and there has been a reduction in leafiness.

Ørskov: At what stage in a breeding programme would you approach farmers to get their views on what they would require in terms of straw yield and quality?

Jenkins: I do not think this would be necessary at any stage in Western Europe.

Gupta: Plant breeding programmes will vary in their priorities in different parts of the world according to the relative importance of crop residues.

SESSION 5

RECOMMENDATIONS AND FUTURE PROSPECTS FOR PLANT BREEDING TO MAINTAIN OR IMPROVE THE NUTRITIVE VALUE OF CROP RESIDUES

REPORTS OF WORKING GROUPS

GROUP 1

Topic: *The effects of crop improvement programmes on the nutritive value and utilisation of crop residues for feeding ruminants.*

(a) Quality

1. Effects of crop improvement programmes on residue quality are probably random. Plant breeders have not, in the past, placed any emphasis on straw and stover quality. This probably applies to all CG Centre programmes and to the NARSs.

   More examples can be found of crop residue quality being reduced than examples of improved residue quality. However, this is probably only because non-adoption of a new variety due to poor crop residue quality is more noticeable than increased adoption because of better stover or straw quality.

   Examples of "improved" varieties with poorer residue quality than locally grown varieties include Beecher barley in the ICARDA region, improved wheats from the Egyptian natural program, and maizes in Mexico.

   The only case of a non-random effect on crop residue quality is that of selecting for bird-resistance in sorghum.

2. The following points were considered to be notable by the group:

2.1 In most crop species there is a large range of digestibility and proportions of plant components.

2.2 Voluntary intake is an important aspect of crop residue quality and must be considered by crop improvement programmes.

2.3 Chemical treatment of crop residues to improve their nutritive value has not been well accepted because of costs, labour requirements, the need to handle toxic chemicals, and unreliable results.

(b) Quantity

In several major cereals the introduction of dwarfing genes has reduced straw quantity, but this effect may be offset by the greater use of fertilizer on dwarf varieties, which increases biomass yield. However, economic factors will not always allow the use of higher inputs, particularly with lower-value crops on resource-poor farms.

It is only desirable to increase the quantity of residues produced in mixed farming areas. In developed countries, where livestock production tends to be concentrated in regions away from crop production, large quantities of crop residues are undesirable.

GROUP 2

Topic: *Factors that limit the nutritive value of crop residues and research that is needed to define and overcome the limitations in nutritive value*

Factors affecting the nutritive value of crop residues

- Level of voluntary intake
- Digestibility
- Animal ability to select leaf material
- Amount on offer
- Anti-nutritional factors

Factors affecting voluntary intake

- Fibre content
- Degradation rate
- Crude-protein content
- Palatability factors

Areas needing research

- Effect of time of harvest on voluntary intake and digestibility of straw
- Effects of storage, particularly with respect to termites, rain damage, use of $NaHCO_3$ under stacks
- Effects of stack construction
- Effects on nutritive value of stress, particularly low soil fertility and drought, and their relationships with phenolics.
- Effect of level of feeding, i.e. what production level represents optimal utilisation of feed resources
- Effect of supplementation with legumes and forages

- Methods for assessing the volume and density of stacks so that the farmer can plan feeding strategies and does not run out of higher quality crop residues because of their higher consumption.
- Evaluation of near-infrared-reflectance techniques, including determination of phenolics and crude protein
- Studies of feed preference and intake
- The NaOH/back titration test for measuring the extent of carbohydrate/lignin bonding needs to be evaluated for different crop species
- Investigation of Maillard reactions in rice straw

GROUP 3

Topic: *The effects of increased utilisation of crop residues for feeding ruminants on productivity, income and stability of smallholder farming systems.*

Crop residues are very important in smallholder systems but in many cases the existing resources are used to the maximum extent. Therefore emphasis needs to be put on increased yield and quality of crop residues and the use of supplements. The trade-offs between use of crop residues as feed or as fuel and construction materials need examination. The increased use of dung as a fuel and its impact on soil fertility should be examined in relation to other sources of fuel, such as multipurpose leguminous trees. The effects of practices such as leaf stripping on fodder and grain yields need studying.

GROUP 4

Topic: *The influence of the amount and value of crop residues on farmers' decisions to grow improved crop varieties.*

These considerations mainly affect integrated crop/livestock systems. The relative importance of crop residues increases with the aridity of the environment. Farmers in higher rainfall areas tend to concentrate on crop production, planting higher-yielding varieties and using more intensive management. Farmers in drier areas tend to derive a greater proportion of their income from livestock and are often adjacent to range areas with substantial livestock populations which may utilise crop residues on a seasonal basis. These generalisations interact with the availability of alternative feed resources and the overall balance of feed resources and livestock numbers.

Crop residues are generally inadequate feed materials and their use in intercropping systems and with supplements needs consideration. However, the adequacy of crop residues as feed depends on the level of production desired, e.g. they may be adequate for non-pregnant, non-lactating animals but unsuitable for production.

Better data are needed on the availability and use of crop residues.

The major aim of crop selection programmes has been to increase grain yield. More experimental work is needed to determine the effect of this on residue quality. Work to date indicates a weakly negative association between grain yield and residue quality in some crops but the poor correlations indicate the possibility of selecting varieties with both higher grain yield and good residue quality.

Ideally, the digestibility of crop residues should be at least 50% but this may not be practicable for some crops. It would also simplify the task of the plant breeder if dual-purpose varieties could be identified i.e. those with good grain yields under favourable conditions but adequate residue quality in all locations. If this cannot be achieved, separate grain and fodder varieties should be identified.

Digestibility and intake may be affected by particular chemicals, such as phenolics, and these need to be characterised. Chemical and biological indicators of crop residue value need to be improved and refined.

GROUP 5

Topic: *Advantages and disadvantages of using crop residues for feeding ruminants in smallholder farming systems.*

Advantages

- o Higher whole-farm income
- o Higher return to cash and non-cash inputs
- o Provides an alternative source of feed to pastures and concentrates
- o Allows the maintenance of animals which would otherwise die reducing the farmers assets

However, these advantages accrue only if feed resources are limiting.

Disadvantages

- o Do not generally allow the use of genetically improved animals
- o Mineral deficiencies
- o Variable intake and digestibility
- o Harvesting, transport and storage problems
- o Legumes and/or chemical treatment may be necessary to make adequate use of crop residues. This may affect the availability of land and other resources necessary for food crops.
- o Alternative end uses of crop residues, including maintenance of soil organic matter, are important. Increased use of crop residues as feed could increase soil erosion or deforestation.

RECOMMENDATIONS

General statement

The international agricultural research centres (IARCs) and the national agricultural research systems (NARS) should recognise that farmers grow crops not only to feed themselves and their families but also to feed their animals. The rejection by farmers of high-yielding varieties because of their low straw yield or poor quality of straw or stover shows that attention must be paid to residue yield and quality in cereal crops.

Specific recommendations

1. Survey data are needed on crop residue use by farmers. Such surveys should involve both agricultural economists and animal nutritionists and aim particularly at understanding farmer perceptions.

2. Collaborative research should study the effects on stability of the farming system of alternative uses of crop residues and manure produced by ruminants fed on crop residues. This should involve crop and animal research institutes and include agroforestry input.

3. Chemical treatment of crop residues has limited applicability to animal production in tropical and sub-tropical countries. Emphasis should be transferred to exploiting genetic variation in crop residue quality.

4. The residues of existing varieties should be ranked in order of nutritive value, such rankings to include comparisons between years

and seasons from crops grown at a range of locations.

5. In ranking crop residues, emphasis should be placed on biological methods, either *in vitro* or *in sacco*. This should be followed by voluntary intake and *in vivo* digestibility measurements and production trials. If near-infra-red reflectance is used to rapidly evaluate larger numbers of samples, it should be linked to biological measurements.

6. Chemical and biological methods of selecting crop residues with higher nutritive value need to be improved and refined. The methods chosen need to be compatible with the objectives of the selection process and the type of crop residue.

7. Variation in the nutritive value of crop residues arises from differences in morphological proportions, variation in cell wall digestibilities, differences in residual cell contents (particularly storage carbohydrates) and anti-nutritional factors, including phenolics. Research should be conducted to determine the relative importance of these variables in different crop species.

8. Intake and digestibility of crop residues is affected by anti-nutritional factors, including phenolics, which need to be characterised using techniques such as high-performance liquid chromatography.

9. The existence of a negative correlation between grain yield and crop residue value has not been proved. Further studies are needed on this subject.

10. IARCs should evaluate the nutritive value of crop residues in advanced breeding lines or populations for all their major mandate crops.

11. IARCs should document the nutritive values of crop residues and forward this information along with information on grain yields to the NARSs.

12. NARSs should test the improved lines for their feeding values and supply data on performance to the relevant IARC for adjustment of lines, where feasible, by plant breeders.

13. A link should be established, in countries where it does not exist, to rapidly pass the crops with improved feeding value to the small-scale farmers through extension staff.

14. Methods of storing crop residues need to be examined to prevent the effects of spoilage on deterioration of feeding value. With improved residues, which may be consumed in higher amounts, methods of assessing the quantities present in stacks would aid farmers in developing feeding strategies.

SESSION 5

RECOMMENDATIONS AND FUTURE PROSPECTS FOR PLANT BREEDING TO MAINTAIN OR IMPROVE THE NUTRITIVE VALUE OF CROP RESIDUES

General discussion

Onim:	We need to arrive at a definition of what constitutes a crop residue. For instance, thinnings may be fed to animals before harvest.
Kossila:	Even materials such as potato peelings are, in my opinion, crop residues.
Said:	Byproducts are mostly fed with supplements, such as urea/molasses, which may influence intake. Clearly the methodology for intake determination needs to be standardised.
Berhane:	I think that the general statement proposed for adoption by the meeting is too strongly worded. I do not believe that the CG centres should put more emphasis on crop residue value.
Van Soest:	The statement does not diminish the importance of grain production in any way. However, it may not be appropriate to list priority crops for investigation of crop residues and there may be many important benefits from a particular variety before residue value should be considered.
Gupta:	Attempts should be made to find morphological characteristics that are associated with feeding values of crop residues.
Jenkins:	It would be useful to have correlated traits with which plant breeders could work.

Van Soest: Whatever selection methods are chosen it is important that they are compatible with the objectives of the work.

Gupta: If the traits related to nutritive value were known even as many as 10,000 samples would not be too large a number in a plant breeding programme. I agree that one should avoid screening entire gene banks.

Jenkins: I believe it would be unwise to be specific on the scale of any evaluation programme.

Van Soest: It is usually necessary to use plant criteria including grain yield to narrow down the number of entries that can be fully evaluated in the laboratory to about 200. Subsequently residues from no more than 12 varieties could be subjected to full animal evaluation. In addition one could include a few parent lines with promising value. Perhaps I should also mention that work on an European Community project being conducted in the Netherlands has shown that varieties of maize grown in Europe have digestibilities of residues 10 units higher than those grown in the USA and this does not appear to be an environmental effect.

Berhane: In my previous comments I was not questioning the practical value of investigating variation in crop residue quality. However I would not see this as a primary responsibility of the CG centres, which should concentrate on grain yield and grain quality. To bring in crop residue value as an index of selection would not serve the immediate mandate of CIMMYT to increase yields of wheat and maize.

Fussell: The question of whether crop residues are important needs to be put to the ultimate user of new varieties, the farmer. More information is needed as to what is happening at the farmer level, through more feedback from extension services.

Witcombe: Ground-level surveys are needed, involving cooperation between economists and animal nutritionists, in order to obtain farmers' perceptions regarding the acceptability of new varieties. This should form a major recommendation.

Little: We need to know the base-line considerations of farmers concerning crop residues.

Onim: There appears to be a need to introduce animal nutritionists at crop research centres.

McAllan: It would concern me that the number of materials to be evaluated may exceed the capacity of animal nutrition facilities. Should animal nutritionists be in a monitoring or collaborative role?

Fussell: I would suggest looking at current varieties first. For example in West Africa only five or six millet varieties would need to be fully evaluated.

Reed: Perhaps we are putting too much emphasis on the need for farmer surveys. For instance we already know that the digestibility of barley straw in the Ethiopian highlands is 55% whereas in Europe it is only 35%. Information is already available for groundnut residues in Senegal. I consider it more important to deal with the effects of crop management on residue values so that they are at least capable of maintaining the animals.

Little: Emphasis needs to be placed on finding an appropriate method of evaluation for particular crops. Subsequently such tests could then be run by laboratory technicians.

Van Soest: I think that one will need more than one parameter to effectively identify varieties with superior crop residue value. The use of plant criteria followed by investigations of crop residue value would seem to be the best means of tackling the large number of entries available.

Jenkins: It would be useful to have contributions from national programme representatives.

Kebede: In Ethiopia I consider that we must continue to give priority to grain production, to consider residue value may be a luxury. Yet this workshop has been an eye-opener and, provided progress is maintained on other aspects of plant breeding, it may well be possible to put together programmes which take into account the nutritional aspects of crop residues.

McDowell: At a recent Centres week, representatives from Africa expressed a preference for hydrids rather than selected varieties. This may relate to yield and quality of residues. For instance in maize stover yields of hybrid varieties were superior to open pollinated varieties.

Witcombe: It is probable that the choice is dictated by the primary economic factors of seed production. I do not think it likely that the quality of stover differs between hybrids and open pollinated varieties.

Pearce: The remaining question is the matter of collaboration between animal nutritionist and plant breeders. Animal nutritionists can distinguish between a number of straws with varying nutritional quality but the input of the plant breeder is needed to tell the animal nutritionist what is practically feasible.

McDowell: The question of the feeding value of crop residues is one that should concern all plant breeders in national programmes as well as the international centres.

Jenkins: The workshop has been most stimulating and may be the first time that plant breeders and animal nutritionists have met to consider the question of crop residues. It is clear that in many situations farmers are interested in the value of these residues. I am sure we would all like to thank ILCA for organising this workshop and Capper and Reed for the original concept.

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