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REVIEW PAPER

GRAIN AND STRAW FOR WHOLE PLANT VALUE: IMPLICATIONS FOR CROP MANAGEMENT AND GENETIC IMPROVEMENT STRATEGIES

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SUMMARY

Straws and stovers are often called 'by-products' of grain production even though they are increasingly important, e.g. for animal feed, thatching, soil improvement, mushroom production and industrial use. As a result, plant breeders, agronomists, economists and animal nutritionists have to pay more attention than before to the total value of crops, i.e. whole plant value in which straws and grain both play a part. This paper reviews literature about the technical potential of breeding and/or management for more or better straw. It then discusses issues of the economic value (EV) and nutritional value (NV) of straw and stovers for livestock feed to guide research and development in cereal breeding and management. It is mainly based on experiences from the Indian subcontinent and semi-arid regions of the Near and Middle East. The paper shows that the quantity and quality of straw produced has changed considerably over recent decades as a result of breeding policies, new cultivation patterns and choice of cultivars. Both EV and NV depend on type of grain, animal production system and access to other feeds. A classification of these factors is provided and suggests that the EV of straw is particularly important in low-input systems with stovers from coarse grains.

INTRODUCTION

The global production of grain has increased dramatically over recent decades through higher yields per unit area and an expanded area under cultivation (Alexandratos, 1995; FAO, 1997). Implicit in this process is that traditional grazing lands are being encroached on for crop production, that fallow periods have shortened, and that the

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world production of crop by-products is increasing (Kossila, 1984; Kelley and Rao 1994; FAO, 1997). All these factors affect the feed supply for ruminants. In turn, these animals provide a range of essential functions for farmers in many farming systems, e.g., draught, dung, security, income. The use of straws and stovers for animal feed has received ample attention from the scientific community. A particularly wide range of chemical treatment and supplementation methods have been examined with varying degrees of success to overcome the nutritional limitations of these 'by-products' and thus to improve farmers' livelihoods (Sundstøl and Owen, 1984; Doyle *et al.*, 1986; Capper *et al.*, 1986, 1988, 1989, 1992; Reed *et al.*, 1987; Schiere *et al.*, 1988; Ørskov *et al.*, 1990; Kiran Singh and Schiere, 1993, 1995; Herbert *et al.*, 1994; Thomson *et al.*, 1993; Doyle and Oosting, 1994; Goodchild *et al.*, 1994, 1996; Joshi *et al.*, 1994; Nordblom *et al.*, 1997). In addition, cereal crop breeders respond to farmers' demands by increasingly considering the economic value (EV) of straws in plant breeding objectives. It is therefore necessary to increase our understanding of the economic rationale of feeding straws, or, in other words, to better assess the EV of straws in relation to grain production.

Two types of fibrous residues of grain crops are distinguished here: straw and stovers. Straw is the residue from the slender-stemmed fine grain crops (e.g. rice, wheat and barley), while stovers are the thick-stemmed residues from coarse grain crops (e.g. maize, sorghum and millet). The potential contribution of straw and stovers to the feed supply of livestock is high indeed when their dry matter yields are translated into what an animal could eat. For example, a grain yield of 3000 kg ha^{-1} of wheat, rice or barley is associated with approximately 4000 kg straw (Kossila, 1984). If a 300 kg animal voluntarily consumes approximately 5 kg of straw dry matter per day (1.7 % of body weight), one hectare of such a crop would provide enough feed for 800 animal days in one harvest! Unfortunately, however, the concentration of digestible nutrients in straw is usually too low to provide enough energy and/or protein to keep animals alive over a long period of time (Sundstøl and Owen, 1984; Owen and Jayasuriya, 1989; Oosting, 1993; Goodchild, 1997). Still worse, new varieties and cultivation methods have been claimed to lead to lower straw yields than before. This idea has been substantiated in some cases, e.g. the genetic potential for straw yield in newly developed varieties of barley, wheat and finger millet was lower than that in old varieties (Riggs *et al.*, 1981; Austin *et al.*, 1980; Gowda *et al.*, 1988) However, it is also possible that recent developments in cereal production have led to higher total biomass yields per unit area due to increased fertilizer use and irrigation that accompanied the introduction of improved varieties. Contrary to common belief, therefore, the total yield of straw per unit area may actually increase due to the effect of increases in the total biomass exceeding those of increases in the grain : straw ratio. For example, varieties 1, 2 and 3 in Figure 1 combine high grain yields with high fodder : grain ratios. Similar results were reported by Powell (1985), Subba Rao *et al.* (1994), Harika and Sharma (1994) and Murthi *et al.* (1994). Grignac *et al.* (1981), however, suggested that 'old' varieties under intensive management show higher total dry matter yields than 'modern' varieties, despite substantially (20 %) lower grain yields. The nutritional quality with regard to energy and protein content of newly developed, often short-stemmed, varieties is

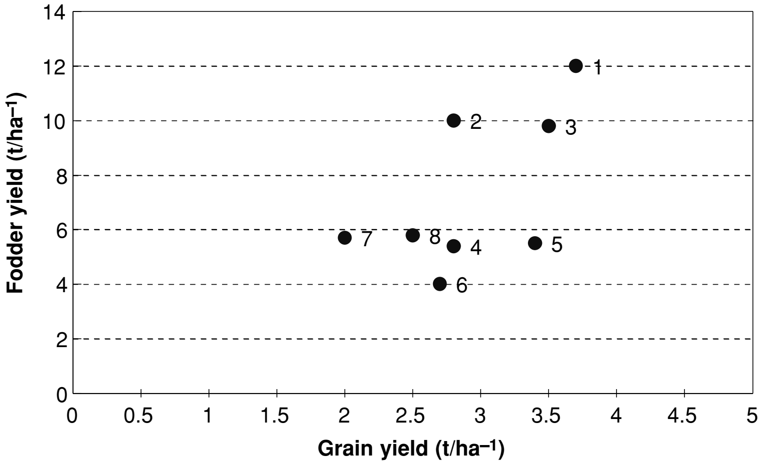


Figure 1. The relation between fodder and grain yield for eight dual purpose sorghum varieties with increasing total biomass yield (based on Murthi *et al.*, 1994). 1 = kharif hybrid CSH 10 (duration 105–110 days); 2 = kharif hybrid CSV 10 (duration 112 days); 3 = kharif hybrid SPV462 (duration 105–110 days); 4 = rabi hybrid CSH 12R (duration 115 days); 5 = rabi hybrid CSH 13R (duration 113 days); 6 = rabi variety SPV 913 (duration 109 days); 7 = rabi variety 'swathi' (duration 117 days); 8 = rabi variety CSV 14R (duration 117 days).

also not necessarily lower than that of the old varieties. This is partly because the leaf : stem ratio generally increases as plants get shorter (Capper *et al.*, 1988; Joshi *et al.*, 1995). Leaves have a higher digestibility and protein concentration than do stems, while leafiness may be associated with increased stem digestibility (Flachowsky *et al.*, 1991).

This paper lists potential improvements in quality and quantity of straw/stover yields that can be achieved through breeding and management. It also lists factors to be considered when discussing the economics of breeding or managing the grain crop for higher straw yields and better straw quality. It explains how these factors differ in importance among farming systems, it sets a framework for discussion by distinguishing different grains and farming systems. It focuses on aspects of plant breeding for more or higher quality straw, and it uses a combination of common sense, anecdotal evidence, thought-experiments and experimental data from the literature. Chemical and physical methods to improve feed quality from straws are not discussed for lack of space and readers are referred to the references mentioned earlier in the text.

VARIATION IN YIELD AND QUALITY OF STRAWS AND STOVERS

Recent work in Asia and the Middle East shows large differences among cereal species and varieties in terms of quantity and quality of straws and stovers. Both plant breeders and cultivators can thus affect the yield of straws and stovers through genetic and environmental factors. Two workshops in India (Joshi *et al.*, 1994; Seetharam *et al.*, 1995) concluded that:

- improvement of straw quality through plant breeding is best done by selection for increased cell wall digestibility and by maintaining or enhancing the 'stay-green' capacity of the crop as some varieties are still green at harvest, thus providing fodder of better quality than varieties that become entirely yellow.
- effects of management tend to interact with genetic effects on straw quality and quantity. Therefore, future research or development work by plant breeders should aim at testing of promising varieties under specific combinations of agro-climatic conditions and cultivation practices (Ceccarelli, 1993).

As an important sideline, this type of work has led to the translation of farmers' criteria into scientists' criteria (Kelley *et al.*, 1991; Anders and Satyanarayana, 1994). Farmers have their own methods to judge straw quality and they often select a cultivar on the basis of grain as well as straw yield, not just by looking at a chemical description, 1000 grain weight and the like. Farmers judge feeding value by criteria such as leaf : stem ratio, stem thickness and texture, sweetness and stay-green quality whereas 'mainstream' scientists use digestibility, sugar content and fibre content (Joshi *et al.*, 1995).

Similar work at International Center for Agricultural Research for the Dry Areas, Syria (ICARDA) on barley improvement for semi-arid regions can be summarized as follows:

- The genetic variability in feeding value (measured as the voluntary intake by sheep) is of the order of 8 % in barley cultivars that have been screened for acceptable grain yields (Goodchild *et al.*, 1996). This is much smaller than the effects of year-to-year variations in weather, climatic zone and management on straw feeding value. The effect of annual weather variations at a single uniformly managed site gave a coefficient of variation of voluntary intake of over 30 % (Goodchild *et al.*, 1996). Maximum air temperature in spring (March to May) appears to be a major weather factor affecting the feeding value of barley straw, contributing at least three times as much to the variance as did rainfall (Goodchild *et al.*, 1998). Values from four years with four different weather patterns (Table 1) illustrate meteorological effects on nutritional value (Goodchild, 1997).
- Genotype x environment interactions occur in the feeding value of barley straw. In years when the barley crop produces a high yield (generally cold, wet years) genotypes adapted to the needs of farmers in semi-arid areas have a better straw feeding value than modern genotypes. In drought years, all genotypes have a reduced grain yield and enhanced straw feeding value, but the effects of drought are smaller in adapted genotypes than in modern genotypes (Goodchild, 1997). Fortunately, the genetic variability in straw voluntary intake is highest in cold, wet years when the coefficient of variation exceeds 10 % (Goodchild *et al.*, 1998). Because of the interaction, barley breeders in semi-arid climates with variable rainfall can have different objectives depending on whether the growing season is relatively cold and wet. Feeding value of straw should be selected for when it is most affected by the environment, i.e. during hot or dry years. Breeders can carry out such selection in dry environments by using tests for nutritional value of straw digestibility.

Table 1. Effects of weather characteristics on the feeding value of barley straw.

Year[†]	Rainfall, February–April (mm)	Maximum temperature, March–May (°C)	Voluntary DM intake ($kg\ d^{-1}$)[‡]	Voluntary ME intake, ($MJ\ d^{-1}$)[‡§]	Crude protein intake, ($g\ d^{-1}$)[‡]	Straw yield ($t\ ha^{-1}$)	Grain yield ($t\ ha^{-1}$)
1992	92	22.6	0.59	3.9	17	c 4.0	3.1
1988	219	22.9	0.63	4.2	11	c 5.0	4.1
1985	95	23.9	0.98	6.1	35	4.6	3.1
1989	24	27.6	1.53	14.1	102	2.2	c 0.1
Maintenance requirement (where DMI = 0.6 $kg\ d^{-1}$)[¶]				6.8	c 56		
Requirement for maintenance and 0.9 kg milk (where DMI = 1.5 $kg\ d^{-1}$)[¶]				14.1	c 169		

[†] Listed in years of ascending order of voluntary intake, not historical sequence.
[‡] For a sheep weighing 54 kg; [§] Metabolisable energy intake, assuming that 1 kg digestible organic matter contains 15.4 MJ (From Goodchild, 1997).
[¶] AFRC (1993).

The correlation between barley straw feeding value and grain yield averaged over four years in 32 genotypes was, if anything, positive (Figure 2). The correlation between feeding value and straw yield was slightly negative, but the genotypic variation in straw yield was less than that in grain yield.

- Genetic improvement of straw grown in favourable conditions would discourage farmers from burning large quantities of low-quality straw, and encourage them to store it for future use (Goodchild, 1997).
- The heritable component of voluntary intake is associated with cell wall digestibility rather than the protein content of straw (Goodchild *et al*., 1996; 1997). Therefore, genetic progress with regard to voluntary intake based on the crude protein content of straw is likely to be slow.
- Barley straw can provide digestible energy to satisfy anything between 60 % of sheep maintenance requirements and the requirements for maintenance and production of 0.9 $kg\ d^{-1}$ of milk (Table 1), but it is unable to supply a matching quantity of crude protein. However, it may be ecologically undesirable to breed for high protein content in straw (even if it were possible), to avoid depletion of soil nitrogen as a side effect of increasing the animals' nitrogen intake. It is more desirable to encourage farmers to grow nitrogen-fixing crops as sources of supplementary nitrogen. These crops may also benefit the soil through their roots and through the manure produced by animals that feed on their foliage or straw.
- It is not certain whether a 'stay-green' character may be present in the crops generally grown in semi-arid areas. But since this character can increase the length of time that the crop transpires, it is likely to reduce soil moisture available for the next crop, and therefore may not be suitable for sustainable agriculture in drier areas.
- Farmers' criteria have been intensively studied in participatory barley breeding trials (Kelley *et al*., 1991; S. Ceccarelli and S. Grando, ICARDA personal comment

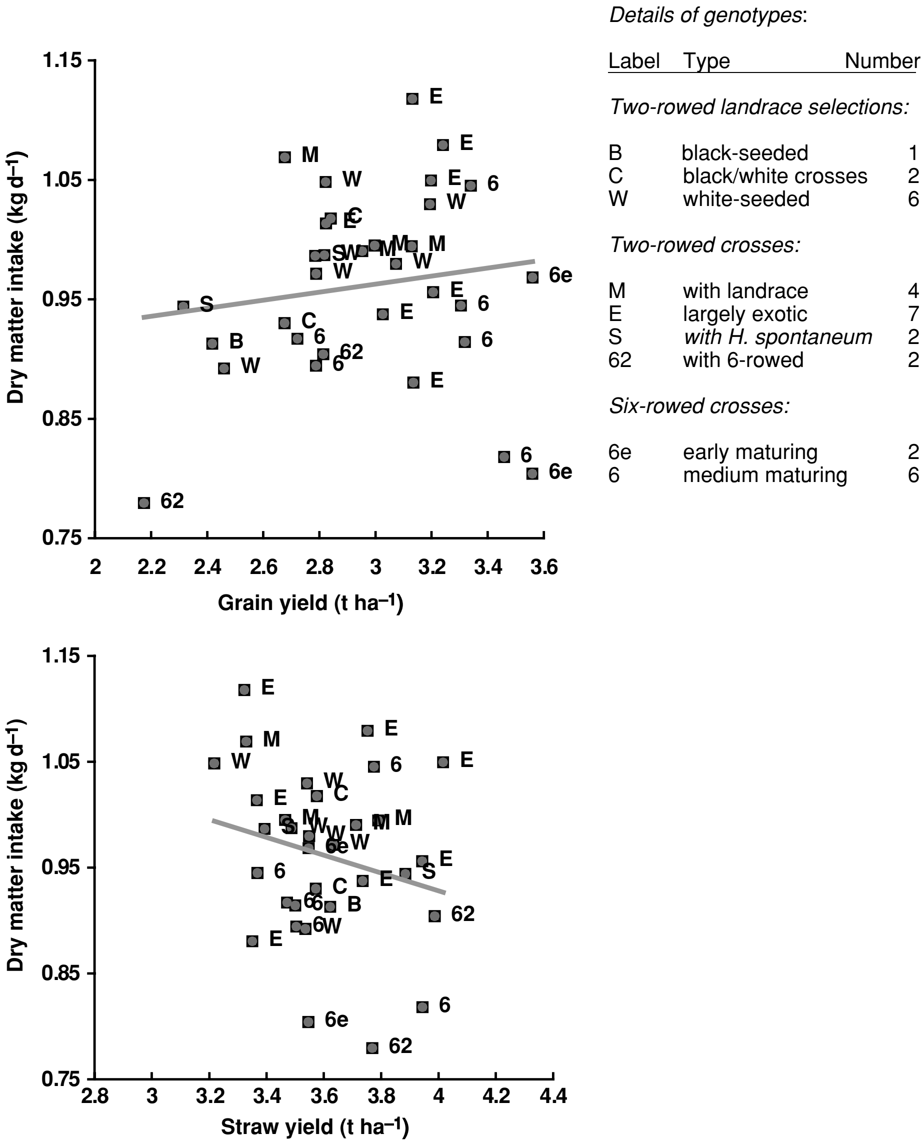


Figure 2. Relation between mean four-year dry matter intake (DMI) of barley straw and corresponding yields of (a) grain (b) straw. Thirty-two genotypes of barley are represented. DMI (kg d^{-1}) is calculated for a 54-kg sheep on the basis of metabolic body size ($kg^{0.75}$). Correlation coefficients (r) for DMI : with grain yield : $r = +0.15$; with straw yield: $r = -0.23$.

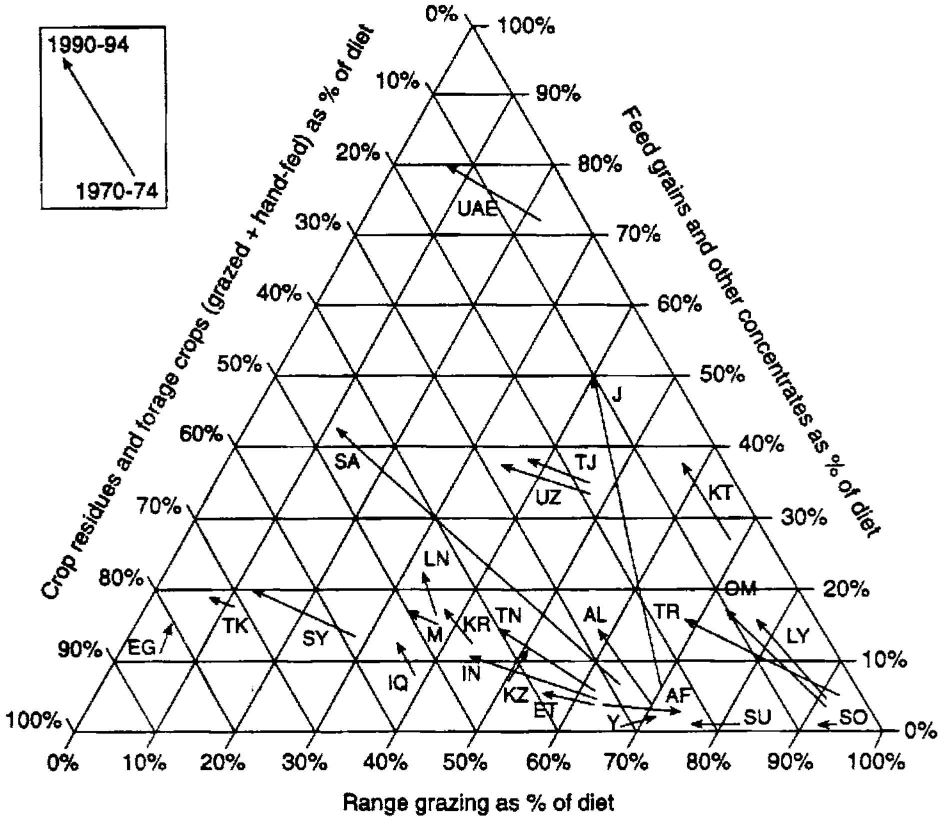
1997). Earlier studies have shown that farmers in risk-prone areas use strategies that maximize total biological yields in dry years. They prefer tall cultivars, which are easier to harvest when shortened by drought, and locally-adapted landrace types of barley, which tend to have the highest grain yields, when affected by drought (Ceccarelli, 1993).

THE VALUE OF STRAW FOR ANIMALS

The total EV of a crop is the sum of the EV of the grains for human consumption and of straws for animal feed, the so-called 'total crop value' (Nordblom and Halimeh, 1982). This is well-recognized by farmers all over the world, but it still tends to be overlooked in many traditional crop improvement programmes. On the argument that food security for the human population was at stake, breeding programmes were formulated too narrowly, only focussing on grain yield and associated parameters (e.g. disease and drought resistance). Indeed, the total value of a crop is also determined by the value of the crop residue for alternative uses. That is not only for animal feeding but also soil for improvement and use for thatching or industry. The latter aspects are not dealt with in detail here because they expand rather than alter the basic argument of this paper that focuses on the value of straws and stovers for animal feed and the characteristics that determine their value.

The EV of straw for feed is a function of both its quantity and quality. If the nutritional value (NV) of straw is zero, its EV for feeding purposes is zero no matter how much of it is produced. In fact, straw and over-mature grasses can have a zero or even negative value as feed. For example, Altona (1966) writes that for African range conditions with over-mature grass resembling straw that 'the animals starve in a sea of plenty'. In such a situation, the animals starve where there is plenty of feed biomass that has very low NV and a negative EV. Farmers' experience and theoretical work such as that by Zemmelink *et al*. (1992) and Schiere *et al*. (1999) show this. Farmers are then better off by discarding part or all of the available low quality roughage, while feeding only the best available feeds to a herd of limited size. This helps to maximize production (milk or meat). And indeed, farmers in some tropical and temperate cropping systems prefer to burn straw rather than to harvest it, seeing this as an easy way to dispose of the straw when the field is to be planted again (Staniforth, 1982; Kelley, 1992).

In many situations, however, feeding of straws and stovers to ruminants makes good sense in spite of the generally low NV. Straw or stover produced during drought tends to contain much of the carbohydrates and the proteins normally allocated to the grains. It may then have a NV equivalent to poor or even medium quality hay. For example, in one year out of 10 in a semi-arid area straw had a digestibility exceeding the average by 10 or more percentage points and a voluntary intake of at least double the average (Goodchild, 1997). Feeding of straw to animals during the dry season keeps them alive so that they can produce meat or milk during the wet season when there is sufficient feed supply. Survival in the lean season also implies that animals can supply draft power during and prior to cropping periods. Even temporary weight loss implies no economic loss to the system over a longer time as long as there is no long-term reproduction loss (Allden, 1970; Schiere and De Wit, 1993). Also, the use of dung for fuel or fertilizer adds value to the straw and it enhances the value of the ruminant for low input systems (Zemmelink *et al*., 1992). In resource-poor conditions, such as drought prone areas, straw can thus be indirectly essential for grain production, but in situations with abundant green feed on roadsides and in forest areas there is no



Key:

AF = Afghanistan; AL = Algeria; EG = Egypt; ET = Ethiopia; IN = India; IQ = Iraq, J = Jordan,
KT = Kuwait; KZ = Kazakhstan; KR = Kyrgizia; LN = Lebanon; LY = Libya; M = Morocco;
OM = Oman; SA = Saudi Arabia; SO = Somalia; SU = Sudan; SY = Syria;
TJ = Tajikistan; TN = Tunisia; TK = Turkey; TR = Turkmenistan;
UAE = United Arab Emirates; UZ = Uzbekistan; Y = Yemen

Figure 3. Livestock diet composition by feed category for selected West Asia and North Africa countries (arrows indicate 20-year trends of five-year averages centred on 1970–1990), after Nordblom *et al.* (1997).

need to feed straw. Overall, where cropland expands at the expense of grazing lands, the feeding of straws and stovers is likely to become more important for animal feed unless energy and nutrients are supplied through fossil fuel and fertilizer (Kelley and Rao, 1994; Figure 3).

ECONOMIC VALUE OF DIFFERENT STRAWS IN DIFFERENT AGRO-ECOLOGICAL ZONES

Straws can thus be both vital and useless as animal feed, for animal production as well as for their indirect impacts on cropping. Such contradiction can be better understood by specifying the importance of different straws and stovers according to agro-ecological and socio-economic criteria. We therefore propose to use two broad criteria for categorising systems. The first one distinguishes between high external input agriculture (HEIA) and low external input agriculture (LEIA) (Schiere and De Wit, 1993), the second between straws and stovers. We hypothesize that feeding of straws and stovers is particularly important in LEIA where also stovers from coarse grains (maize, millets and sorghum) tend to predominate.

The difference in EV of straws between HEIA and LEIA can first be illustrated by the price ratio between grain and straw as calculated for rice in a HEIA system and finger millet in a LEIA system (Table 4). In semi-arid LEIA systems, in particular, concentrates or green fodder tend to be unavailable or uneconomical for feeding to animals that are not kept primarily as income generators. Straw then becomes a relatively valuable feed and in emergency situations, it can even have an extremely high EV to secure survival of the animals. This holds even more in LEIA systems with high climatic risks where the loss due to a failed grain harvest can be partly compensated by using the straws as animal feed (Nordblom *et al.*, 1997). Another difference between HEIA and LEIA regions refers to the distinction between stovers and straws. Stovers from crops such as sorghum and millet are mostly grown in LEIA and straws from wheat, rice and barley in HEIA (Purseglove, 1972). Importantly, the NV in terms of digestible energy of stovers tends to be better than that of straws (Prasad *et al.*, 1993). When grown under similar conditions stovers from coarse straws tend to have lower NV, but the generally more restricted grain fill in coarse grains due to more unfavourable conditions leaves more NV in the stovers. A third difference is that LEIA agriculture tends to be conducted in agro-ecologies with less alternative employment than HEIA agriculture. Total plant value is likely to be more relevant in these conditions. We feel that these discussions warrant the hypothesis that NV and EV differ among grain and farming systems and that feeding of fibrous crop 'by-products' is particularly important for stovers and under LEIA conditions.

QUANTITATIVE INFORMATION

Several data sources and anecdotal evidence support the earlier statements. The first point is that there is evidence of straw being or becoming economically more valuable in the course of time. Kelley *et al*. (1991) and Murthi *et al*. (1994) show that in India the contribution of sorghum stover to the economic output of agriculture is the same as or sometimes even exceeds that of sorghum grain (Tables 2 and 3). Also, long-term trends show increased dependence on crop residue feeding in many countries (Figure 3) and even an increasing straw : grain price ratio e.g. for sorghum (Figure 4). One of the authors (JBS) has further frequently observed that farmers across the Indian sub-continent recall that straw was once burned, while it is now increasingly fed and/or used for bedding. In a recent analysis of rural development in West Africa, de Ridder *et al*. (2003) identified a similar trend in that region. The trend that straws represent an increasingly important part of total crop value is at least sufficiently illustrated to be taken seriously as a working hypothesis.

Table 2. Sorghum grain and fodder yields with associated value of production, All India, Maharashtra and Andhra Pradesh data, average of three years (1987–1989), based on Kelley *et al.*, 1991.

Data	Average Yield ($100\ kg\ ha^{-1}$)†		Average Value (Indian Rs ha^{-1})‡		Total value of crop (Rs ha^{-1})	Fodder value % of total crop value
	Grain	Fodder	Grain	Fodder		
All India						
Variety	31.1	110	4920	4720	9640	49
Hybrid	37.8	106	5970	4540	10 510	43
Maharashtra						
Variety	38.2	112	6000	4810	10 900	45
Hybrid	43.1	102	6820	4380	11 200	39
Andhra Pradesh						
Variety	22.3	108	3680	4860	8540	57
Hybrid	33.5	110	5520	4940	10 460	47

† Average of dry matter yield of 16–20 'improved' (variety) genotypes from at least 30 locations each year for All India, 14 locations for Maharashtra and five locations for Andhra Pradesh.
‡ Based on hybrid grain and fodder post-harvest (December) prices, @ Rs. 158 and Rs. 43 per 100 kg, respectively for All India and Maharashtra and @ Rs. 165 and Rs. 45 for Andhra Pradesh (various sources).

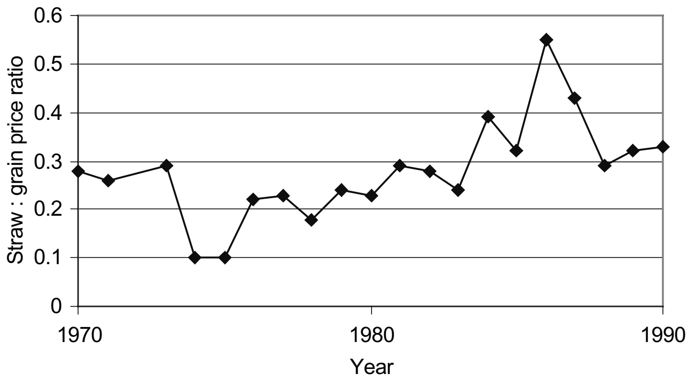


Figure 4. Annual change in the sorghum straw : grain price ratio at Solapur market (India), based on Kelley *et al*. (1991).

The second point is that large differences occur in EV and NV within and between straws and stovers. For example, Figure 5 shows different EVs of straw types in the state of Haryana in India (De Wit *et al*., 1993). No increase in EV of straw was found in Haryana over time, except perhaps for a slight increase for millet stover. Importantly, however, this location in India is different from the situation illustrated in Figure 4 as it refers to an area with predominantly HEIA systems where more green feed is produced than in other regions of India. To complicate matters, the differences among straws are confounded by seasonal effects, since the wheat straw in this region becomes available in April-May, when feed shortages are higher than around the rice harvest (October-November). In addition, the rice is harvested in a period of relative labour shortage and there is pressure for the next cultivation. This leads to burning of rice

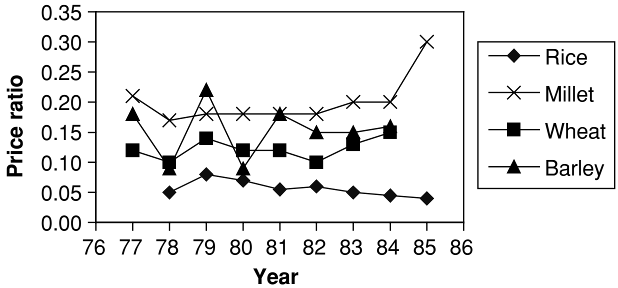


Figure 5. Ratios of straw : grain price (Rs kg^{-1}) for four different cereal straws over a 10-year period (1977–1985) in Haryana, India.

Table 3. The relative importance of grain yield, stability of grain yield, stover and straw production and quality, and green fodder production within grain sorghum and wheat production systems in three major agro-climatic zones in India.

Crop	Agro-climatic zone	Grain yield	Stability of grain yield	Straw/stover yield†	Straw/stover quality	Green fodder
Sorghum	Low rainfall, erratic (Gujarat, Andhra Pradesh, Maharashtra)	++	+++	+++	+	NA
	Assured rainfall (Gujarat, Andhra Pradesh, Maharashtra)	++	+	+	+	+
	Irrigated (Punjab, Haryana)	NA	NA	NA	NA	NA
Wheat	Low rainfall erratic	NA	NA	NA	NA	NA
	Assured rainfall	++	++	++	+	NA
	Irrigated	+++	++	++	+	+++

+ to +++ Minor to major.
NA Not applicable.
† The importance of straw yield is upset in mechanised harvesting due to a loss of straw and there is a need to adjust the machinery to minimise these losses.

straw in those areas, even when the NV of rice straw in terms of digestibility and intake tends to be the same or even slightly 'less bad' than that of wheat straw (Prasad *et al*., 1993). Importantly, straw NV does therefore not always represent EV.

The combination of NV and EV differences among straws and stovers and between HEIA and LEIA is reflected in Table 4. It compares two widely different farming systems, i.e., with rice in HEIA (Northern India), and with finger millet in LEIA around Bangalore (South India). A major point in this calculation is that for coarse grains the value per kg grain is lower and the straw : grain ratio higher than for small grains. The data in Table 4 agree well with the observations that stover value can be as high as 50 % of total crop value as shown in Table 2 and by Murthi *et al*. (1994).

Indeed, the value of the fibrous by-products relative to grain appears to be higher for stovers than for straws, and higher in LEIA than HEIA. However, even straws of rice and wheat can have a sufficiently high EV to influence cropping patterns in HEIA, whether used for animal feed or industrial purposes. The first author has often

Table 4. Calculation of the relative contributions of straw and grain economic value to total crop economic value in a high yielding fine grain (rice) for high external input agriculture and in a low yielding coarse grain (finger millet) for low external input agriculture conditions.[†]

	Rice	Finger millet
Grain yield (kg ha^{-1})	5000	1000
Straw yield (kg ha^{-1})	8000	3000
Straw/grain ratio	1.60	3.00
Price of grain (Rs kg^{-1})	5.00	2.00
Total value of grain (Rs)	25 000	2000
Price of crop residue (Rs kg^{-1})[‡]	0.40	0.60
Total value of crop residue (Rs)	3200	1800
Total crop value (Rs)[§]	28 200	3800
Contribution of grain to total crop EV (%)	89	53
Contribution of straw to total crop value (%)[§¶]	11	47

[†] The values are based on reasonable estimates during 1994–1995 for South Indian conditions (Karnataka State).
[‡] The value of crop residues is difficult to establish except under specific conditions. In high input systems, straw can be a nuisance, thus lowering the estimate used (0.40 Rs kg^{-1}); in low input systems straw can be highly valuable if it makes the difference between survival and collapse of the farm. Even if straw in such cases is not traded, the estimate of Rs 0.60 kg^{-1} might underestimate its real value in terms of farmer perceptions, which would in reality increase its contribution in total crop value.
[§] Deduction of other costs (fertiliser, labour) from total value will increase the EV of straw as a proportion of total revenue, but this must be offset against the costs and opportunity costs of harvesting straw, and the loss in EV of the straw associated with *e.g.* chemical spraying or mechanical harvesting.
[¶] If grain cannot be harvested (more likely in finger millet than in rice systems) the relative value of straw becomes 100 %.

seen that in urban dairies the straw dry matter is sold at prices exceeding the price of concentrate, and in spite of the higher NV of concentrate in terms of digestible energy and protein content. Obviously, straw in this case has qualities that concentrate does not have. When fed in relatively small quantities to animals on otherwise high concentrate rations, straw buffers and maintains rumen functioning and preserves the fat content of the milk. In green fodder-growing HEIA systems, such as in the Gangetic plains and the Nile delta, straw is routinely fed mixed with highly digestible forage to provide better rumen function and/or to expand the number of animals that can be fed (De Wit *et al*., 1993). In another example, a Rapid Rural Appraisal (RRA) in a HEIA situation in West Bengal (India) indicated that a rice variety with a shorter growing season would allow cultivation of an additional vegetable crop. The farmers, however, rejected this technology because it would restrict straw availability for their animals (S. Mukhopadhyay, personal communication, 1993). Also, some Punjabi farmers are said to generate higher revenues per unit area of a certain wheat variety than of other varieties when they count revenues from both straw and grain (S. Nagarajan, personal comment, 1995). Many more cases are recorded where farmers include the EV of straw or stover as a criterion in their choice of cultivar. Farmers in the Indian States of Maharashtra and Andhra Pradesh are reported to be aware of the effect of grain variety on straw quality and quantity, expressing 'quality' in terms of stem thickness, stay-green or sweetness (Anders and Satyanarayana, 1994; Kelly and Rao, 1994).

From many other parts in the world similar reports and economic analyses are available (Reed *et al*., 1987; Joshi *et al*., 1994). For example, the high grain yielding Beecher barley variety was rejected by Syrian farmers because of its generally poor straw quality (Capper *et al*., 1986; 1988). Jansen *et al*. (1990) even assume that the demand for fodder from stover around Indian cities is a reason for the slow adoption rate of modern sorghum varieties. Modern INDAF varieties of finger millet were rejected by farmers in Karnataka and Andhra Pradesh (Seetharam *et al*., 1995), and it is said that as long as 20–30 years ago, wheat breeders in India were told by the farmers to pay more attention to straw yield (Kiran Singh, personal communication, 1995). Traxler and Byerlee (1993) show that particularly in LEIA areas, the straw EV is an important criterion to reject or accept new cereal varieties. Last but not least, some farmers in LEIA conditions plant their crops densely in order to use the thinning for animal feed, a prime example of agronomic practices being adjusted to ensure maximum total crop value of grain and fodder. (Byerlee *et al*., 1989).

PRACTICAL CONSEQUENCES AND REMAINING ISSUES

Quantity and quality of straw and stover have thus been shown to be likely to become an increasingly important consideration in the selection or rejection of cereal cultivars and agronomic practices. Qualitative reasoning and quantitative evidence have been presented to substantiate the need for more attention to the EV of straw. This paper focuses on the use of straw and stover for animal feed, but it stresses that considerations of soil management, harvesting practices and industrial use should not be forgotten. Variation in the relevance of straw may be attributed to differences among farming systems (HEIA and LEIA) as well as among straws and stovers. Farmers themselves may identify further causes of variation, whether gender issues, farmer's status, local soil type or the possibility for intercropping. We like to mention a few particular issues for future plant improvement strategies. The first one refers to agronomic practice, in which it is possible to plant for grain and fodder rather than for grain alone, e.g. by planting more densely or by planting very densely for subsequent thinning (Joshi *et al*., 1995). The thinnings are fed to cattle and some reduction in grain yield is accepted when necessary. Thinning is a practice reported by many authors, e.g. for maize in Punjab (Byerlee *et al*., 1989), for jute in Northeastern India (Singh and Saha, 1995) and for millets in Ethiopia (Kassa Belay, 2003). In a way, this strategy resembles the grazing of a winter grain in spring for better tillering and an early harvest of some fodder as done in some Middle Eastern and European countries, but with completely different time scales. Second, more work can be done on the value of straw for animal survival (Allden, 1970; Zemmelink *et al*., 1992; Zemmelink and 't Mannetje, 2002), on the value of straw for non-feed purposes (Hartley *et al*., 1987), and on the use of straw primarily for soil improvement and/or animal bedding (Grossbard, 1979; Lal, 1988; Oomen *et al*., 1995). Thirdly, but equally important, the mutual adjustments of crop and livestock sub-systems to ensure maximum total system output is an issue (Patil *et al*., 1993). The choice of animals can be 'adjusted' to realize maximum advantage of crop residues and *vice versa*, *e.g*., denser planting leads to thinner straw and better feeds. These topics are too broad for elaboration here, but they cannot be ignored in future work that gives due recognition to the fact that straw is an integral part of the total plant value.

CONCLUSIONS

Reasoning, common sense, field observations and published data suggest that large variations occur in EV and NV of straws and stovers. In LEIA systems with coarse grains, in particular, it is increasingly important to assess the performance of a crop on the basis of whole plant value. Agronomists and plant breeders are thus to consider aspects of quality and quantity of straws and stovers for animal feed when embarking on plant improvement programmes. Farmers themselves already choose and manage their crop so as to get more and/or better straw, when relevant for their farming system. Farmers are far more aware than scientists of the economic value of straw even though their criteria may be different. At the same time, it is possible to 'translate' farmers' criteria into those of scientists and *vice versa* and much progress in that area should be possible. Also, less unnecessary loss of economic and nutritional value from straws due to narrow focus on grain yield may increase adoption rates for new cereal varieties. Genetic variability in nutritional value and quantity of straws and stovers is likely to be less than variability due to environmental effects and cultivation practices, and they might only be useful in specific scenarios e.g. when the genotypes with desirable straw or stover characters are also those that are adapted to climatic stresses. We hypothesise that choices are to be made, among others based on the distinction between HEIA and LEIA, which combine choice of crops and environmental effects. The second factor for priority setting in large-scale programmes is the difference between straws from fine grains and stovers from coarse grains. In particular, the stovers from coarse grains tend to constitute a product with more value than straws. The stover biomass is a relatively larger part of total plant biomass, the unit price for grains from millets, for example, tends to be lower than that of rice and wheat, and crop failures in riskier LEIA conditions are more likely, thus leaving at least stover as a product to be sold or fed. Economic work should help to analyse the details of the total plant value in general and of the EV of straws in particular. Collaboration is essential between economists, agronomists, animal scientists and, last but not least between formal research and farmers (men and women). Not only should the focus be on straw-or-stover and grain for human and animal feed, but also on aspects such as use of straw for soil improvement or for industrial purposes. Agronomists should consider maximising total crop value rather than just food grain production, and they should therefore reconsider traditional approaches in planting densities and cropping strategies. Fortunately, grain and straw yield are not as mutually exclusive in production as one tends to believe. Priorities for (funding of) plant breeding programmes may have to be reconsidered, particularly with respect to the extra value of stovers in LEIA conditions, and the indirect effect of stover quantity and quality on grain yield and the need for other inputs, such as cultivated fodder or concentrate feeds.

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