Animal Nutrition and Feed Technology (2004) 4 : 1-15

Sorghum and Pearl Millet as Food-feed-crops in India

A. Hall[1], M. Blümmel[2*], W. Thorpe[2],
F.R. Bidinger[3] and C.T. Hash[3]

[1]Natural Resources Institute, University of Greenwich
Chatham Martime, Kent ME4 4TB, UK

[2]International Crop Research Institute for the Semi-Arid Tropics (ICRISAT)
Patancheru 502 324, India

[3]International Livestock Research Institute (ILRI), c/o ICRISAT
Patancheru-502 324, India

(Received November 18, 2003)

ABSTRACT

This paper reviews the role of and demand for food-feed-crops, that is crops that are grown to provide both grain for human food and crop residues as fodder for ruminant livestock. The paper argues that the predicted increase in demand for livestock products will coincide with shrinking common property resources and an increasing scarcity of arable land and water resulting in an increase in the importance of food-feed-crops smallholder crop-ruminant livestock systems. As a consequence, the International Crop Research Institute for the Semi-Arid Tropics and the International Livestock Research Institute have implemented collaborative research on the genetic improvement of fodder value of food-feed-crops, with emphasis on sorghum and pearl millet, which are important crops for the rural poor. The research has demonstrated the existence of significant genetic variation for fodder quality traits and it has identified cultivars that provide superior stover quality and quantity without detriment to grain yield. Initial estimates of heritability of pertinent stover quality traits were in the order of 0.7 suggesting good opportunities for further improvement of stover quality by genetic enhancement. However, certain socio-economic conditions need to be met for large-scale uptake of new varieties and hybrids.

Key words : Sorghum, Pearl millet, Stover quality, Genetic improvement.

Reprint request: Dr. M. Blümmel, Tel: +91-8455-282498; Fax: +91-40-23241239;
E-mail: m.blummel@cgiar.org

INTRODUCTION

The improvement of the livelihoods of poor livestock farmers and their families is the core mission of the International Livestock Research Institute (ILRI) and its partners. South Asia, West Africa and the East African Highlands are home to large concentrations of poor livestock keepers (Thornton *et al.* 2001) and consequently these are key targets for ILRI's work. Livestock rearing can provide a pathway out of poverty through improvements to household nutrition, cash income, asset building and employment (McIntire *et al.*, 1992; Sansoucy *et al.*, 1995; de Haan *et al.*, 1999). It is highly probable that by exploiting the opportunities represented by the increasing demand for livestock products in developing countries (Delgado *et al.*, 1999), that even higher benefits can accrue for poverty reduction from livestock in the years to come. In many parts of the developing world, and especially in South Asia, West Africa and the East African Highlands, livestock productivity is closely linked to the quantity and quality of available fodder, much of which is sourced from food crops. These seasonally available fodders are generally inadequate in quantity and quality, particularly in rain-fed systems and during extended dry seasons, presenting a serious constraint to livestock productivity (Renard, 1997). Most of the livestock keepers targeted by ILRI and its partners are resource poor crop-livestock farmers with very limited access to arable land and water, conditions that limit allocation of arable land exclusively for the purpose of fodder production (Renard, 1997). Declining and deteriorating common property resources further reduce access to fodder aggravating the nutritional deficit and reducing livestock productivity.

The pressure from the increased human population, intensifying cropping systems and greater crop-livestock integration has translated into farmers increasingly requiring crops that provide not only good grain or pod yields but also more reliable and better quality fodder. Whether in South Asia (Kelly *et al.* 1996, Underwood *et al.*, 2000, Rama Devi *et al.*, 2000), West Africa (Kristjianson *et al.*, 2002 and Singh *et al.*, 2003) or East Africa (Desta *et al.*, 2000; Romney *et al.*, 2003), the demand expressed by poor crop-livestock farmers for improved food-feed crops is well documented. By combining the gains from selection for grain, pod and forage components, food-feed crops can contribute to improved resource use and systems efficiencies that will help alleviate fodder constraints without additional demands on scarce agricultural resources such as arable land and water, since these are in any case required inputs for grain and pod production. Furthermore, the delivery of food-feed crop technologies to farmers' fields can be greatly aided by short deliver pathways since the private and public players in the seed industry are developing at an encouraging rate in South Asia (Govila *et al.*, 1997; Hall and Yogand, 2000) and elsewhere. In response to the demand for - and the opportunities offered by - food-feed crops, collaborative work was initiated between ILRI and its sister institute the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) to improve the fodder value of sorghum and pearl millet stover through multi-dimensional crop improvement programs. This paper briefly reviews the demand for sorghum and pearl millet with emphasis on India and discusses the progress made towards developing improved food-feed-crop genotypes. The paper also addresses the problems encountered and outlines some socio-economic conditions that favour or limit the large-scale adoption of improved food-feed-crop genotypes.

Sorghum (*Sorghum bicolor*)

Case studies in India

Traditionally sorghum has been of critical importance in the crop-livestock systems of the semi-arid regions of India. Current production area is 12 million hectares and it is the third major crop after rice and wheat and accounts for about 16% of the world sorghum production (Dayakar Rao, 2000). However, over the last 20 years significant declines have taken place in both area of production and the consumption of sorghum as food. In understanding these changes it is important to recognize that while both rainy season sorghum and post-rainy season sorghum are important sources of stover (the dry leaf and stem residues fed to livestock following the harvest of the grain), the evolving scenarios effecting each is quite different with very distinctive production zones and consumption characteristics.

Rainy season sorghum has witnessed the greatest declines in production – particularly through replacement by more profitable crops, particularly oilseed. The introduction and adoption of hybrid rainy season sorghum has increased productivity, but also has allowed the area of production to be reduced while maintaining production levels. Hybrids have been criticized for inferior grain and fodder qualities. Traditional rainy season varieties remain popular in more marginal rainy season sorghum production zones. However lack of technical change in these areas has seen crop replacement with more profitable crops. Cropping pattern changes and climatic variability have seen increasing fodder scarcity in the rainy season sorghum production zone. Post-rainy season sorghum production has been stable although still registering some decline. It is grown on residual moisture in deep black soil areas (vertisols) for which few other crop production options exist. Little technical change has taken place; preferred varieties are at least 50 years old. Post-rainy season sorghums are low yielding, but have grain types with preferred food qualities and attract a substantial premium. Recent studies (Underwood *et al.*, 2000; Hall and Yogand, 2000) have comprehensively explored and documented the importance of sorghum for livelihoods in the context of changing production and consumption scenarios. These studies reveal that the role of sorghum in the livelihoods of poor remains both important, particularly in years of poor rainfall, and complex. Its importance relates to both its direct contributions of more and cheap food and feed, particularly in low rainfall years, as well as through indirect contributions through income (sale of grain and stover) and employment. Sorghum is a typical food-feed-crop in that grain and stover are of similar importance to household economies. Rama Devi *et al.* (2000) estimated that sorghum stover utilization as fodder and in fodder trading contribute up to 50% to household income in sorghum cropping areas in India.

Hall and Yoganand (2000) point out that employment is often the most critical livelihood concern of the poor who, in the sorghum production areas of India, are often at best marginal farmers and usually landless. They go on to argue that it's the sustainability of the farming system – including sorghum production – that is the greatest source of livelihood via the employment derived from agriculture. The importance of sorghum is thus as an input into these farming systems through its role as an animal feed -- in many areas sorghum contributes at least 50% of livestock diets. (Underwood *et al,* 2000). Maintaining the viability and improving the efficiency of these integrated, sorghum-based crop-livestock systems is a strategy that will support the livelihoods of the poor. Hall and Yoganand (2000) estimate that in this way sorghum remains important in India particularly in rural areas with a population of at least 60 million people and 20 million cattle and buffaloes.

Variability in sorghum stover fodder value

Joint research between ILRI and ICRISAT on food-feed crop properties of sorghum genotypes concentrated initially on genotypes grown in the rainy season (Kharif) in India and the main findings of this work were recently summarized (Blümmel *et al.*, 2003a/b). In brief, significant genotypic differences in fodder quality of stover of 12 popular dual-purpose and grain hybrid sorghums grown under

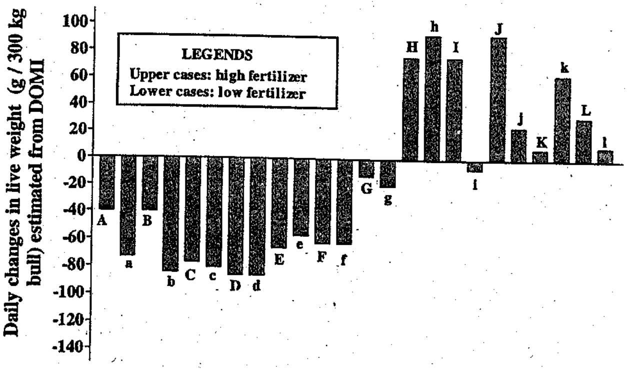

Fig. 1. Daily changes in live weight of bulls fed sorghum stover from 12 cultivars estimated from regression analysis of organic matter intake and organic matter digestibility and live weight changes in sheep. Modified from Blümmel *et al.*, 2003a/b).

high and low fertilizer input were observed when tested as sole feed in experimentation with bulls. *In vivo* organic matter digestibility varied from 44.8 to 56.1 and from 45.3 to 54.6% under high and low fertilizer application, respectively, while digestible organic matter intake ranged from 19.5 to 29.2 g/kgLW$^{0.75}$ under both fertilizer applications. Daily changes in live weight in bulls were estimated based on digestible stover intake and relationship developed from digestible organic matter intake and changes in live weight in sheep fed un-supplemented barley straws (Blümmel *et al.*, 2003a). These predicted live weight changes are presented in Figure 1.

The data presented in Figure 1 should be interpreted with some caution because these changes in live weights were not measured but predicted. Nevertheless, the relative differences between genotypes in supporting animal performance presented in Figure 1 probably hold true, and the genotypic variability in sorghum stover quality is substantial. Interestingly, the grain hybrid CSH 16 (represented by H and h in Fig. 1) with the highest grain yield also performed very well in the feeding experiment. No significant relationship was observed between estimated changes in live weight and either grain or stover yields; stover quality and grain yield and stover yield seem to be compatible traits. In this context highest observed grain yields were in the order of 3.5 to 3.8 t/ha and stover qualities in these high yielding varieties were found at the low (DOMI = 20g/kgLW$^{0.75}$) and the high (DOMI = 28 g/kgLW$^{0.75}$) end of observed DOMI. Similarly DOMI from 19.5 to 29.2 g/kgLW$^{0.75}$ could all be associated with stover yields of more than 10 t/ha (Blümmel *et al.*, 2003a/b). Ranges in stover yields in these twelve genotypes were 6.1 to 18.1 and 5.0 to 16.2 t/ha under high and low fertilizer application, respectively. It is important to realize that sorghum stover is heavily traded for fodder with a quality dependent price of about 1300 to 2800 Indian Rupees per ton (Blümmel and Walyiar, unpublished observation on sorghum stover trading in Hyderabad, Andhra Pradesh). The observed ranges in stover quality and stover quantity will, therefore, have direct implications for livelihoods in sorghum growing areas.

However, the relationships between grain and stover yield and stover quality, may differ in sorghum grown in the off-season (Rabi). While improved sorghum varieties and hybrids were highly adopted for Kharif cropping, little adoption of such genotypes was observed in Rabi season cropping, and there is a need for more research to improve food-feed-crop rabi-type sorghums. In an ongoing collaboration between the National Research Center for Sorghum and ILRI, 83 Rabi genotypes (49 varieties and 34 hybrids) in various stages of the releasing process of the All India Coordinated Sorghum Improvement Project, were recently investigated for stover crude protein content and *in vitro* digestibility (Ravi *et al.*, 2004). Stover crude protein content was significantly associated negatively with grain yield in both varieties and hybrids; the negative association was much less severe in varieties (R^2

= 0.1, P = 0.02) than in hybrids (R^2 = 0.66, P < 0.0001). The relationship between crude protein and stover yield was significantly positive for varieties (R^2 = 0.27, P < 0.0001) but insignificant (P = 0.32) for hybrids (Ravi *et al.*, 2004). *In vitro* digestibility of stover and grain yield were also inversely associated (see Figure 2a) with a slightly stronger association observed for hybrids (R^2 = 0.42) than for varieties (R^2 = 0.38).

Despite these inverse associations between desirable traits observed in the rabi-type sorghum, scope does exist for selecting Rabi sorghum genotypes with superior food-feed-crop characteristics. For example, in the ranges of very high grain yields of about 4 t/ha, *in vitro* digestibility of stover varied between *c.* 41 and 49% and between 45 and 54% in hybrids and varieties, respectively (Fig. 2a). Digestible stover yield (the product of total stover yield times its digestibility) and grain yields were not significantly associated but for the hybrids the relationship tended (P = 0.09) to be inverse (Fig. 2b). High grain yields (c. 4 t/ha) could be associated with digestible stover yields between *c.* 1.5 to 3.3 t/ha and between 2 and 4.7 t/ha in hybrids and varieties, respectively (Fig. 2b).

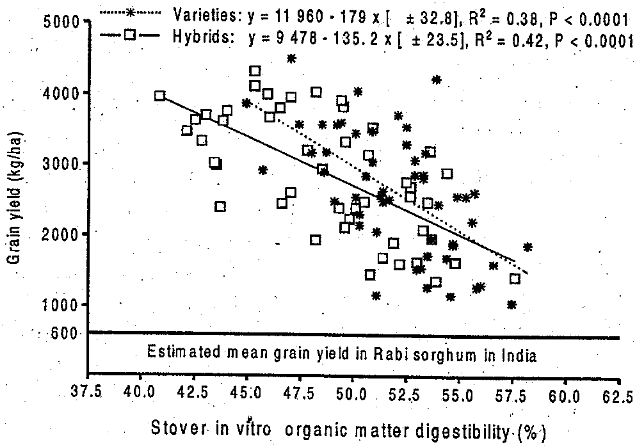

Fig. 2a. Relations between stover *in vitro* digestibility and grain yield in 83 genotypes of Rabi sorghum

The inverse relationships between stover *in vitro* digestibility and grain yield (Fig. 2a) are probably due to moisture stress and associated limitations in nutrient supply under off-season growing conditions. These conditions will result in arrested translocation of nutrients such as protein and soluble carbohydrates from the stem into the grain with the overall effect of stems having higher nutritive quality by

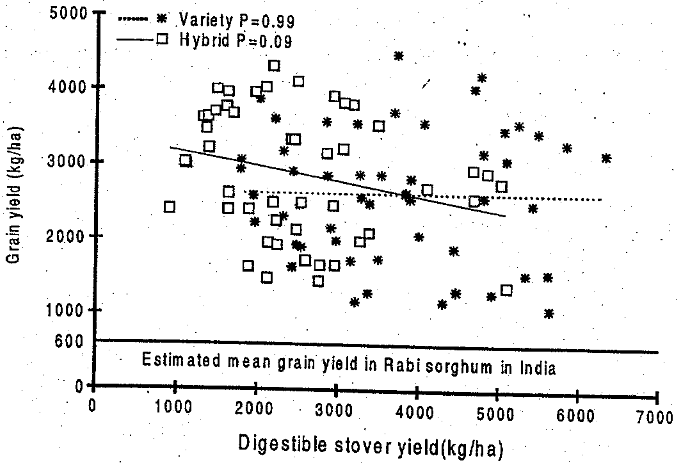

Fig. 2b. Relation digestible stover yield and grain yield in 83 genotypes of Rabis orghum

reduced grain yield. More work appears to be required to investigate stover-grain relationship under limited input systems. For example, mean grain yield in Rabi sorghum in India is about 600 kg/ha. These mean yields are well below the yields observed in the genotypes from the All India Coordinated Sorghum Improvement Project (Fig. 2a/b). This might reflect the superiority of the improved genotypes compared to cultivars grown by farmers but is may also reflect better conditions and higher inputs on the experimental fields of the NRCS.

Pearl millet (*Pennisetum glaucum*)

Importance of pearl millet stover

Pearl millet is the most drought tolerant of all domesticated cereals. It can yield grain under seasonal rainfall as low as 200 - 250 mm (Bidinger and Hash, 2003) making it the only reliably productive cereal in the driest rain-fed regions of the arid and semi-arid tropics. Nearly 70% of the Indian pearl millet area (>9 million hectares) is sown to hybrid seed with most of this purchased by farmers with land holdings <5 ha (Govila *et al.*, 1997; Talukdar *et al.*, 1999). This seemingly incongruous use of hybrids by some of the world's poorest agriculturists is a result of two factors: first, farmers can recover seed costs with a modest 10% gain in grain yield (~70 kg ha^{-1} at average on-farm yield levels), and secondly, hybrid is readily available because seed multiplication, distribution, and marketing are very profitable, due the high demand for hybrid seed, high seed multiplication rates, and a highly effective contract hybrid seed production system. In addition to pearl millet's role as the major source of calories in human food in areas in which it is widely grown, its stover constitutes a major component of ruminant rations in marginal production environments, particularly during the dry season when green fodder/grazing resources are limited. The nutritional quality of millet stover is relatively poor however, and supplies are often inadequate, both of which are linked to the low productivity of livestock in smallholder crop-livestock systems in these environments (Renard, 1997).

Practices that might improve stover yields and stover quality, such as higher applications of nitrogen (currently averaging only 5-20 kg ha^{-1}, as both manure and mineral fertilizer) are considered very risky for farmers to adopt in such highly unpredictable, drought-prone environments. The best option for increasing the availability and quality of crop residues appears to be genetic improvement of both these characteristics in currently available cultivars. Such cultivars, which have characteristically been bred only for a high grain yield, are considered by farmers to have an inferior stover quality, in comparison to adapted, but lower yielding, traditional landraces (Kelly *et al.*, 1996). Considering the growing demand for more and better quality fodder for livestock, pearl millet improvement programs need to become multidimensional, targeting the whole plant rather than one single trait.

Genetic variation in stover quality

Blümmel *et al.* (2003a, b) investigated the ruminant nutritional quality of six prominent cultivars of pearl millet grown under low (9 kg/ha) and high (90 kg) nitrogen fertilizer, in similar feeding trials with bulls to those previously described above for sorghum. Stover organic matter digestibility in bulls varied among genotypes from 40.1 to 48.1% and from 45.3 to 51.3% under high and low fertilizer application, respectively. Daily digestible organic matter intake ranged from 17.9 to 23.8 g/kgLW$^{0.75}$ and from 16.6 to 20.8 g/kgLW$^{0.75}$ under high and low fertilizer application, respectively. Despite these differences among cultivars, however, no cultivar had sufficient stover quality (at either fertilizer level) when fed without supplementation, to meet animal maintenance requirements, as all estimated changes in live weight of bulls were negative (Fig. 3). In addition, estimated changes in live weight in bulls and grain yield among genotypes tended ($P < 0.1$) to be inversely associated in this study, suggesting that the simultaneous improvement of both grain yields and animal performance may be difficult to achieve. These data also show that fertilizer application does not necessarily improve pearl millet stover quality.

These initial conclusions were re-evaluated in a recent, more comprehensive study involving a greater number (30) of more genetically variable genotypes of pearl millet (divided equally among arid zone landraces, improved open-pollinated varieties and high yielding hybrids), which were grown at three very different locations in India (Gwalior, Nagpur and Patancheru). Genotypes differed significantly for biomass, grain and stover yields, and for stover nutritional quality characteristics (Table 1). The range in genotype means for stover digestibility was significant (39

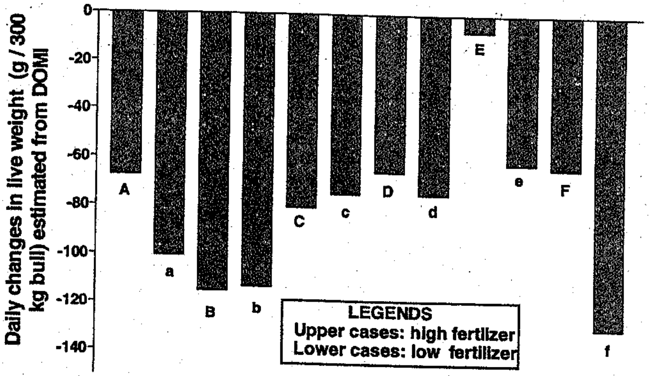

Fig. 3. Daily changes in live weight of bulls fed pearl stover from six cultivars estimated from regression analysis of organic matter intake and organic matter digestibility and live weight changes in sheep. Modified from Blümmel *et al.*, 2003a/b).

Table 1. Overall means, ranges in individual cultivar means, and entry mean heritabilities for pearl millet *in vitro* stover digestibility, stover total and digestible yields and predicted digestible stover intake by sheep in comparison to similar values for biomass yield, grain yield biomass harvest index. Data are from a 30 - entry pearl millet trial grown at three locations in 2001. (**$P<0.01$, *** $P<0.001$).

Variable	Mean	Cultivar range	Heritability
Stover *in vitro* digestibility (%)	40.5	39.2 to 41.9 ***	0.71
Stover yield (kg/ha)	3480	2350 to 4440 ***	0.66
Digestible stover yield (kg/ha)	1380	900 to 1840 **	0.69
Digestible stover intake (g/kgLW$^{0.75}$/d)	27.8	24.5 to 31.7 ***	0.62
Biomass yield (kg/ha)	6180	4680 to 7030 **	0.37
Grain yield (kg/ha)	1760	1070 to 2230 ***	0.71

to 42%), but smaller than that in the initial experiment, but the range in digestible stover yields was large (900 to 1800 kg/ha), due to a large range in stover yield (Table 1). Digestible dry matter intake (estimated by a combination of Near Infrared Spectroscopy, laboratory traits and *in vivo* experimentation with sheep) ranged from 25 to 32 g/kgLW$^{0.75}$/d, which was both larger than that in the initial study and overall significantly higher with sheep than with bulls (Table 1). Heritabilities for all stover quality and yield traits were of the same order as that for grain yield (0.6 to 0.7), which is sufficiently high to expected useful progress from selection for improved stover quality traits (Table 1).

It is interesting to note that estimated genotypic variations in digestible organic matter intake were much greater (24.5 to 41.9 g/kgLW$^{0.75}$/d) than ranges in *in vitro* digestibility, which were narrow (39.2 to 41.9%), see Table 1. These data appear to suggest that actual variation in livestock productivity will be greater than suggested by a single laboratory quality estimate.

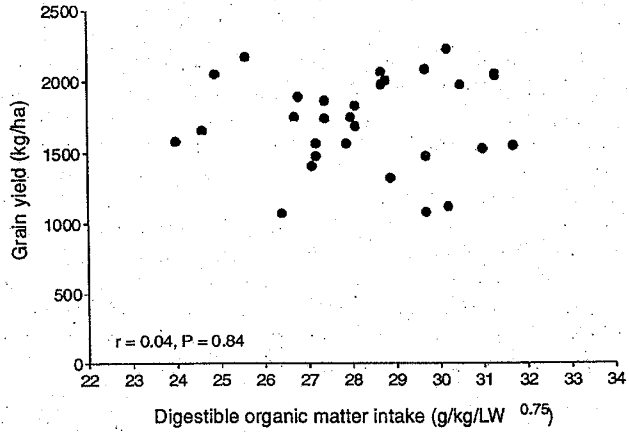

Fig. 4a. Predicted digestible organic matter intake an grain yield in stover from 30 genotypes of pearl millet grown at three locations in India.

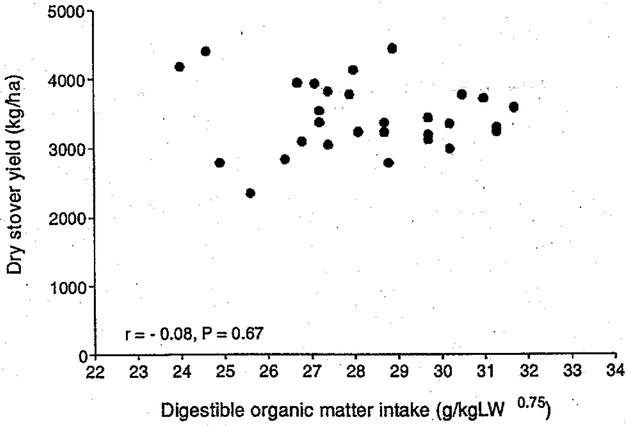

Fig. 4b. Predicted digestible organic matter intake and stover yield from 30 genotypes of pearl millet grown at three locations in India

Most encouragingly and in contrast to the initial study, there were no inverse relationships between digestible organic matter intake and either grain or stover yields (Blümmel *et al.*, 2003c, Figure 4a/b).

In summary, this more comprehensive study indicates that there is useful and heritable genetic variation in important stover quality traits in pearl millet, and a high degree of independence between stover fodder value and grain yield over a wide range of genotypes and evaluation environments confirming that there is the opportunity to improve both traits in breeding programs seeking to do this. With nearly 70% of the Indian pearl millet area sown to modern hybrids, the improvement in the quantity and/or the nutritional quality of the stover of these hybrids could make a significant impact on livestock productivity in millet-growing areas. In response to this opportunity, ICRISAT and ILRI have initiated research on dual purpose top-cross hybrids, generated from both grain and dual-purpose pollinators and fodder-type male sterile lines, to provide private hybrid seed industry with improved parental lines that convey higher stover quality without sacrificing grain and stover yield (Blümmel and Rai, 2004).

Prospects for technology adoption

The evidence suggests that sufficient and useful genetic variability exists to allow the development of both dual purpose sorghum and millet varieties and hybrids with improved fodder value. Improved fodder value is a characteristic of high relevance to the current scenario in the sorghum- and millet-based crop-livestock systems of India. In coming years the rising demand for livestock and livestock products is likely to increase this relevance. If this potential is to be translated into technology development and adoption a number of things need to be considered.

Firstly the nature of Indian seed systems dictates that the most effective technology diffusion channels are likely to be through the private sector seed industry. Indeed this is already starting to happen through the work described at ICRISAT involving a partnership with a consortium of private seed companies (Blümmel and Rai, 2004). The industry is well developed with effective mechanisms for distributing seed and it is sensitive to the production, consumption and market characteristics preferred by farmers (Reddy *et al.* 2001). The important role of the private sector means that improved feed characteristics will be incorporated into hybrids rather than varieties because of the obvious commercial interest of the industry. While private (and public) sector hybrids represent a significant proportion of area of production (more so for pearl millet, less so for sorghum), there are still large areas where open pollinated varieties are used and preferred. There are a number of reasons for this including food preference in the case of sorghum. However in general these tend to be lower rainfall, more marginal production areas (Hall and Yoganand, 2000) where fodder shortages are most acute and thus where the need for varieties with improved feed characteristics are greatest (Underwood *et al.* 2000). Varieties represent a lower production risk as the seed is cheaper than hybrid and often home saved, and varieties often perform better than hybrids in low rainfall conditions. The use of varieties rather than hybrids is most marked in the case of sorghum and at present only rainy season hybrids have been developed and widely promoted. The post-rainy season crop consists entirely of open pollinated varieties.

While inclusion of improved feed characteristics into varieties presents no greater obstacles than inclusion in hybrids, the diffusion and adoption of varieties is constrained in a number of ways. For example in some areas farmers have not adopted a new rainy season sorghum variety for over twenty years (Underwood *et al.* 2000). For post-rainy season sorghum the preferred variety is at least 50 years old. Underlying this are a number of issues related to the suitability of improved varieties to the more marginal and complex production environments where varieties are preferred. In part the poor suitability of varieties relates to a crop improvement research process that on the one hand is often insensitive to production, consumption and cropping system concerns of farmers, and on the other hand struggles to cope with the complexity and diversity of production contexts that vary from location to location and from year to year.

There are now increasing calls to tackle this problem through participatory research where by farmer are involved at an early stage in evaluating varieties and influencing choice of shaping plant and grain characteristics. While often assumed to be simply an add-on to conventional plant breeding techniques, participatory approaches have fundamental institutional implications that have by and large not been addressed by public breeding programmes. Critically the approach suggests that the whole plant breeding, variety evaluation and seed production and distribution systems would need to be decentralized to allow a greater role for farmers, and a sharper focus on micro production contexts. It would also require the identification of appropriate organizations or agencies to manage these activities at the local level and that this would in all likelihood require partnership with private entrepreneurs and or development agencies from the government or non-government sectors.

There is clearly a need to further explore ways in which participatory breeding and local seed production systems could be strengthened. Since these questions can only be answered empirically, pilot initiatives should be used to test and evaluate alternatives. This is critical if valuable characteristics such as improved feed quality are not only going to be incorporated into varieties, but also that the varieties are effectively diffused to farmers. While hybrids developed in collaboration with the private seed industry have an extremely valuable role to play in supporting small-scale farmers, it will be improved varieties and innovative seed systems that contribute to the welfare of the poorest farm households in the most marginal areas.

CONCLUSION

The research reviewed in this paper demonstrated the existence of significant genetic variation for fodder quality traits and identified cultivars that provide superior stover quality and quantity without detriment to grain yield. Initial estimates of heritability of pertinent stover quality traits were in the order of 0.7 suggesting good opportunities for further improvement of stover quality by genetic enhancement. However, certain socio-economic conditions need to be met for large-scale uptake of new varieties and hybrids.

REFERENCES

Bidinger, F.R. and Hash, C.T. 2003. Pearl Millet. In: *Integration of physiology and molecular biology in plant breeding* (Eds. H. Nguyen and A. Blum). Marcel Dekker, New York (in press).

Blümmel, M. and Rai, K.N. 2004. Observations on stover quality, stover quality-grain yield relationships and heterosis effects in 52 cultivars of pearl millet. *International Sorghum and Millet Newsletter* (in press).

Blümmel, M., Zerbini, E., B.V.S. Reddy, Hash C.T., Bidinger F. and Ravi D. 2003a. Improving the production and utilization of sorghum and pearl millet as livestock feed: methodological problems and possible solutions. *Field Crops Research,* 84: 123–142.

Blümmel M, Zerbini E., B.V.S. Reddy, Hash C.T., Bidinger F. and Khan A.A. 2003b. Improving the production and utilization of sorghum and pearl millet as livestock feed: progress towards dual-purpose genotypes. *Field Crops Research,* 84: 143-158.

Blümmel M., Bidinger F.R., Zerbini E., Raj A. G.B. Chauhan G.S. and Hash C.T. 2003c. GxE effects and heritability for traits related to stover ruminant nutritional value of 30 diverse pearl millet cultivars (*American Society of Agronomy,* Denver, November 03, conference contribution accepted).

Dayakar Rao, B. 2000. Factors affecting the production and Utilization of sorghum at the farm level. In: *Sorghum utilization and the livelihoods of the poor in India: Summary Proceedings of a Workshop* (Eds. A.J. Hall and B. Yogand), 4 –5 February, 1999, India: Socioeconomic and Policy Program, International Crop Research Institute for the Semi-Arid Tropics, Patancheru, India, pp. 49–55.

de Haan, C., Steinfeld, H and Blackburn, H. 1999. *Livestock and the Environment: Finding a Balance.* European Commission Directorate-General, Development Policy Sustainable Development and Natural Resources, Commission of the European Communities, Food and Agricultural Organization of the United Nations, World, Bank. Fresigfield, Eye, Suffolk, UK, p. 115.

Delgado, C., Rosegrant, M., Steinfeld, H., Ehui, S., and Courbois, C. 1999. *Livestock to 2020: The next food revolution.* International Food Policy Research Institute, Food and Agriculture Organization of the United Nations, and International Livestock Research

Institute. IFPRI Food, Agriculture and the Environment Discussion paper 28, Washington, DC, p. 72.

Desta, L., Kassie, M., Benin, S. and Pender, J. 2000. *Land degradation and strategies for sustainable development in the Ethiopian Highlands: Amhara Region.* Socio-economic and Plocy Research Working Paper No. 32, Intenational Livetsock Research Institute, Addis Abeba, Ethiopia.

Govila, O.P. Rai, K.N., Chopra, K.R., Andrews, D.J. and Stegmeier, W.D. 1997. Breeding pearl millet hybrids for developing countries: Indian Experience, *Proceedings of the International Conference in Genetic Improvement of Sorghum and Pearl Millet,* 23 to 27t Sep. 1996, Lubbock Texas. INTSORMIL Publication No. 97-5. USAID Title XII Collaborative Research Support Program on Sorghum and Pearl Milllet: Lincoln Nebraska, USA, pp. 97–118

Hall, A.J. and Yogand, B. 2000. *Sorghum utilization and the livelihoods of the poor in India: Summary Proceedings of a Workshop.* 4–5 February, 1999. International Crop Research Institute for the Semi-Arid Tropics, Patancheru, India, p. 92.

Kelly, T.G., Parthasarathy Rao, P. and Weltzien, R.E., 1996. Adoption of improved cultivars of pearl millet in an arid environment, straw quality and quality considerations in Western Rajastahn. *Experimental Agriculture,* 32: 161-171.

Kristjanson, P., Tarawali, S., Okike, I., Singh, B.B., Thornton, P.K., Manyong, V.M., Kruska, R. L. and Hoogenbom, G. 2002. *Genetically improved dual-purpose cow-pea: Assessment of adoption and impact in the dry savanna region of West Africa.* ILRI, Nairobi, p. 67.

McIntire, J., Bourzat, D. and Pingali, P. 1992. *Crop-Livestock Interaction in Sub-Saharan Africa.* The World Bank, Washington, DC, p. 246.

Rama Devi, K., Bandyopadhyay, R., Hall, A.J., Indira, S., Pande, S. and Jaiswal, P. 2000. *Farmers' Perception of the Effects of Plant Diseases on the Nutritive Value of Crop Residues used for Peri-Urban Dairy Production on the Deccan Plateau: Findings from Participatory Rural Appraisals.* Information Bulletin No. 60. International Crop Research Institute for the Semi-Arid Tropics, Patancheru, India.

Ravi D., Vishala A.D., Nayaker N.Y., Seetharama N. and Blümmel M. 2004. Grain yield and stover fodder value relations in 83 varieties and hybrids of off-season (Rabi) sorghums. *International Sorghum and Millet Newsletter* (under revisison).

Reddy, B.V.S, Hall, A.J., and Rai K.N. 2001. The long road to partnership: private support of public research on sorghum and pearl millet. In: *Sharing Perspectives on Public-Private Sector Interaction. Proceedings of workshop* (Eds. A.J. Hall, B. Yoganand, V. Rasheed Sulaiman and N.G. Clark), *April 10.* International Crops Research Institute for the Semi Arid tropics, Patancheru, India and National Centre for Agricultural Economics and Policy Research, p. 44 (ISBN 92-90066-437-1).

Renard, C. 1997. *Crop Residues in Sustainable Mixed Crop/Livestock Farming Systems.* CAB International, Wallingford, UK.

Romney, D.L, Thorne, P., Lukuyu, B. and Thornton, P.K. 2003. Maize as food and feed in intensive smallholder systems: management options for improved integration in mixed farming systems of Eastern and Southern Africa. *Field Crops Research* (in press).

Sansoucy, R., Jabbar, M.A., Ehui, S. and Fitzhugh, H. 1995. The contribution of livestock to food security and sustainable development. In: *Livestock Development Strategies for Low Income Countries, Proceedings of the Joint FAO/ILRI Roundtable on Livestock Development Strategies for Low Income Countries* (Eds. R.T. Wilson, S. Ehui and S. Mack),. 27 February- 2 March 1995, ILRI, Addis Ababa, Ethiopia, FAO/ILRI, Nairobi, Kenya, pp. 9-21.

Singh, B.B., Hartmann, P., Fatokun, C., Tamo, M., Tarawali, S.and Ortiz, R. 2003. Recent progess on cowpea improvement. *Chronica Horticulturae,* 43: 8-12.

Talukadar, B.S., Khairwal, I.S. and Rattan Singh. 1999. Hybrid breeding. In: *Pearl Millet Breeding* (Eds. I. S. Kairwal, K. N. Rai, D. J. Andrew and G. Harinarayana), Oxford & IBH, New Delhi, India, pp. 269-301.

Thornton, P.K., Kruska, R.L., Henninger, N., Kristjianson, P.M., Reid, R.S., Atieno, F., Odera, A. and Ndega, T. 2001. *Poverty and Livestock Mapping: Final report to the UK Department for International Development,* August, 2001. International Livestock Research Institute, Nairobi, Kenya.

Underwood, M.P., Hall, A.J. and Zerbini, E. 2000. *Genetic enhancement of sorghum and millet residues fed to ruminants: Farmers' perception of fodder quality in livelihood systems.* Summary report of PRA case studies in Andhra Pradesh, Gujerat, Maharashtra, Karnatka and Rajasthan states. International Livestock Research Institute, Nairobi, Kenya and International Crop Research Institute for the Semi-Arid Tropics, Patancheru, India, p. 68.