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Abstract

Abstract Lignocellulosic biomass from forest, agricultural wastes and crop residues is the most abundant renewable biomass on earth, with a total production estimated to range from about 10-50 billion metric tonnes annually (Sanchez and Cardena, 2008). About 3.8 billion metric tonnes are contributed by crop residues, with cereals contributing 74 percent, sugar crops 10 percent, legumes 8 percent, tubers 5 percent, and oil crops 3 percent (Lal, 2005). Considering the huge quantities of crop residues available from agricultural production, it comes as no surprise that attempts to upgrade crop residue biomass for livestock fodder reach back to the beginning of the 20th century (Beckmann, 1921). These and later attempts included chemical, physical, and biological treatments, but comparatively little uptake of these technologies was observed, despite considerable effort by the international research and development community (Owen and Jayasuriya, 1989). Lack of adoption of post-harvest approaches to improvement of crop residues stimulated a new research paradigm of targeted improvement of crop residues pre-harvest by plant breeding and selection at source. It was in the mid-nineties that the International Livestock Research Institute (ILRI) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) started to explore simultaneous improvement of grain and crop residue traits as a major cross-CGIAR collaborative project. Initially more attention was given to typical rain-fed crops such as sorghum, pearl millet, maize, groundnut and cowpea than to crops such as rice and wheat which, in the Indo-Gangetic Plains, are usually grown in irrigated areas. Several special issues were dedicated to dual purpose work with these rain-fed crops (Lenné et al., 2003, Sharma et al., 2010; Blümmel et al., 2013) concluding that significant variation in livestock feed traits exists among cultivars and that this variation can be exploited without detriment to grain yields. Rice and wheat are important crops for global food security. Rice is a staple for nearly half of the world's population, many of whom live in Asia, and wheat is the staple for 35% of the world's population. Non-grain residues, that is the straws of these crops, represent an important asset for livestock producers as a feed resource and it is important to understand the uses, tradeoffs, and possibilities for pre-harvest improvement of the nutritional quality and yield of these straws. This special issue brought together research that describes the status and future opportunities that exist for improving the quality of wheat and rice straws. Papers included describe research on market conditions for rice and wheat straw, traders' perceptions on nutritional quality, opportunities for simultaneous improvement of grain yield, straw yield and straw fodder quality in rice and wheat and finally, crop management options. The special issue contains a total of 14 papers, 6 reporting work from India, 2 each from South Asia and China and 1 each from Turkey, Ethiopia, Philippines and Australia.

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Dear Jill

Please find attached revised version of **Recent Advances in Dual Purpose Rice and Wheat Research: a synthesis**"

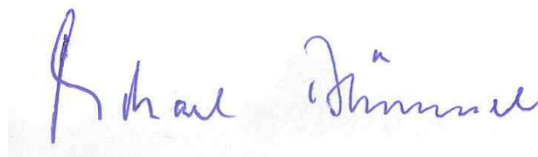
Revised were:

- Level of details in summary were reduced
- New paragraphs were introduced
- References in the Agronomic Use section from the US were added
- A concluding section was added

With the hope that this revision is acceptable

Greetings

Michael Bluemmel

A handwritten signature in blue ink that reads "Michael Bluemmel". The signature is written in a cursive style with a large initial 'M' and a distinct 'B'.

Recent Advances in Dual Purpose Rice and Wheat Research: a synthesis

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Abstract

Lignocellulosic biomass from forest, agricultural wastes and crop residues is the most abundant renewable biomass on earth, with a total production estimated to range from about 10-50 billion metric tonnes annually (Sanchez and Cardena, 2008). About 3.8 billion metric tonnes are contributed by crop residues, with cereals contributing 74 percent, sugar crops 10 percent, legumes 8 percent, tubers 5 percent, and oil crops 3 percent (Lal, 2005). Considering the huge quantities of crop residues available from agricultural production, it comes as no surprise that attempts to upgrade crop residue biomass for livestock fodder reach back to the beginning of the 20th century (Beckmann, 1921). These and later attempts included chemical, physical, and biological treatments, but comparatively little uptake of these technologies was observed, despite considerable effort by the international research and development community (Owen and Jayasuriya, 1989). Lack of adoption of post-harvest approaches to improvement of crop residues stimulated a new research paradigm of targeted improvement of crop residues pre-harvest by plant breeding and selection at source. It was in the mid-nineties that the International Livestock Research Institute (ILRI) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) started to explore simultaneous improvement of grain and crop residue traits as a major cross-CGIAR collaborative project. Initially more attention was given to typical rain-fed crops such as sorghum, pearl millet, maize, groundnut and cowpea than to crops such as rice and wheat which, in the Indo-Gangetic Plains, are usually grown in irrigated areas. Several special issues were dedicated to dual purpose

work with these rain-fed crops (Lenné et al., 2003, Sharma et al., 2010; Blümmel et al., 2013) concluding that significant variation in livestock feed traits exists among cultivars and that this variation can be exploited without detriment to grain yields.

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Providing the context

Before embarking upon any large-scale improvement venture through plant breeding, clear evidence is needed to support the effort. Samireddypalle et al. in their study "*Embracing whole plant optimization of rice and wheat to meet the growing demand for food and feed*" (this volume) pointed out that feed scarcity resulted in large yield gaps in livestock production in low- and middle-income countries (LMIC). In India, for example, the feed deficit in terms of digestible crude protein and total digestible nutrients is estimated to be 50 and 60%, respectively. Feed supply scenarios in India suggest that on a dry matter basis, crop residues (i.e. straws, stovers, and haulms, the byproducts from grain production) contribute about 70% of feed resources. Crop residues are

therefore the single most important feed resource in India, a scenario that likely holds good for many LMICs. The authors argued that crop residues and crop by-product-based feeding systems have the advantage of low direct and indirect competition with food production, since no or few grains are fed to livestock and no land or water had to be exclusively allocated to feed production.

Using cropping and land use patterns, rice and wheat yields, and harvest indices to calculate rice and wheat straw yields and livestock census and herd structures, Samireddypalle et al. concluded that, in India in 2016, the mass of rice and wheat straws potentially available as fodder were about 113 and 78 million tonnes, respectively, contributing about 67% of all the cereal straws. Using three scenarios, a 10% increase in rice and wheat straw yield (scenario 1), a 10% increase in rice and wheat straw metabolizable energy (ME) concentration (scenario 2) and a combination of the two (scenario 3) the paper estimated that for the whole of India the additional potential milk and meat production (excluding maintenance requirements) from the additional ME from rice and wheat straw in scenarios 1 or 2 would be equal to 27.6 million tons of milk or 9.2 million tons of mutton and the corresponding figures in scenario 3 would be 58.2 and 19.4 million tons, respectively. The authors concluded that considerable opportunity exists in whole plant optimization of rice and wheat, based on collaborative work by plant and animal scientists for mitigating feed shortages in LMICs. The authors also prepared the ground for more targeted demand for dual-purpose rice and wheat by disaggregating the contribution of these straws to feed resources in individual Indian states. While on a national level rice straw contributed 21.9% to dry matter feed resources the contribution was as low as 0.9% in Rajasthan and as high as 58.7% in Assam. Wheat straw contributed 15.1% to feed dry matter in India with the contribution being negligible in many Southern states but reaching 43.7% and 38.9% in Haryana and Punjab, respectively.

While the preceding study provided evidence that breeding efforts have the potential to improve livestock feed and nutrient availability in LMIC, evidence is also needed on the economic benefit

resulting from a crop improvement program. In their survey “*Rice and wheat straw fodder trading in India: Possible lessons for rice and wheat improvement*” Duncan et al. (this volume) quantified volume and price of wheat and rice straw traded in Northern India. The authors argued that rice and wheat straw fodder market transactions would provide solid and objective information about the monetary value of straws and the extent to which traders distinguish between straws based on fodder quality. These findings would provide valuable inputs for decisions on including or rejecting straw traits in rice and wheat improvement programmes. Their survey covered 17 trading locations in the cities of Patna and Hajipur in 2008- 2009. and showed that traders had their own system for informally classifying straws based on sensory characteristics. There was reasonable agreement between the traders’ quality classes and specific sensory traits. Average *in vitro* digestibility (IVOMD) of rice and wheat straw were 40 and 46.3%, respectively, and wheat straw traded on average for prices around 19 % higher than rice straw. Within species, differences in laboratory nutritive value between straw quality classes were small. There were significant correlations between price and laboratory nutritional traits although these primarily related to differences between rice and wheat rather than differences within a crop species. Across the crop species the best relationship between laboratory traits and straw prices were found for acid detergent fiber $P = 0.0007$) and IVOMD ($P = 0.002$). Straw N was not significantly ($P = 0.06$) related to straw prices.

Findings on dual purpose rice

Large genetic variation exists in rice, which is exploited to meet a range of growing and management conditions. Rice is produced under upland and paddy conditions, leading to potential variation in straw production, quality and management. Evaluation of the potential breeding efforts to improve yield and quality of rice straw for livestock feed requires understanding on the variability in trait expression, correlation of feed traits to grain traits and heritability estimates. A series of studies addressing these issues are reported in this special issue. Traditional methods of laboratory

evaluation of straw quality have been slow and cumbersome. To speed the advancement of breeding for improved feed traits, improved and rapid methods of quality evaluation are beneficial. Several papers addressed this issue for rice.

Virk et al. in their paper "*A note on variation in grain and straw fodder quality traits in 437 cultivars of rice from the varietal groups of aromatic, hybrids, Indica, new planting types and released varieties in the Philippines*" (this volume) investigated a comprehensive set of different rice types and cultivars for grain yield (GY), straw nitrogen (N) content, neutral (NDF) and acid (ADF) detergent fiber, acid detergent lignin (ADL), silica, IVOMD and ME and for relationships between GY and these straw fodder quality traits. Highly significant ($P < 0.0001$) differences between the types were observed for all traits, with hybrids having the highest GY and also having the highest mean straw N, IVOMD and ME. Variations in GY and straw fodder quality traits were greater within cultivars than between cultivar types. The variations in straw quality traits between cultivars were significant in terms of livestock nutrition. For example, key straw quality traits such as IVOMD varied between cultivars by at least 6.9% units in new planting types and up to 12.0% units in varieties. Some of the cultivars with superior GY also had superior IVOMD and the authors concluded that cultivar differences in rice straw quality can be exploited without detriment to GY, since inverse relationships were largely absent.

Similar findings were reported by Subudhi et al. in their paper "*Genetic variation for grain yield, straw yield and straw quality traits in 132 diverse rice varieties released for different ecologies such as upland, lowland, irrigated and salinity prone areas in India*" (this volume). The authors investigated rice varieties released for different ecologies such as upland (25) and lowland (26), irrigated (65) and salinity affected (16) areas over two consecutive years for GY and SY, straw N, NDF and ADF, ADL, silica and IVOMD. Highly significant ($P < 0.0001$) differences were found between the cultivars for all traits, though between-year differences were also significant except for one trait (NDF) indicating GxE effects. As in the preceding paper, cultivar differences in key traits like IVOMD

were substantial, varying by up to 7.4 percent units. Similarly, the cultivar with the highest IVOMD was also the 3rd highest in terms of grain yield. High GYs in the range of 6000 to 6500 kg/ha were associated with straw N contents ranging from approximately 0.7 to 1.0%.

The authors reasoned that where targeted genetic enhancement of straw traits was the objective, the most immediate straw trait to be improved would be SY. Grain yield and SY were strongly ($P < 0.0001$) positively correlated, though the former accounted for only 31% of the variation in the latter. Rice improvement targeting areas where rice straws contribute significantly to livestock feed resources should therefore record total biomass yield, as well as GY. The h^2 for SY was 0.71 and should support breeding for high SY. Moderate to intermediate h^2 of 0.30 to 0.52 were observed for the traits IVOMD, N and NDF, and these h^2 should also allow for targeted genetic enhancement since these straw quality traits have a genetic foundation. However, the authors cautioned that the mode of genetic inheritance of rice straw fodder quality traits seems complex, since positive and negative heterosis for straw digestibility had been reported. Slightly below mid-parental rice straw digestibilities have been reported but also insignificant relationships between mid-parental values and those of F1.

Ravi et al. investigated widely-grown rice varieties for grain-straw traits in their paper "*Investigation of fifteen popular and widely grown Indian rice varieties for variations in straw fodder traits and grain-straw relationships*" (this volume). The 15 popular rice cultivars were investigated over two years for GY and SY, harvest indices (HI), straw N, NDF and ADF, ADL, Silica, IVOMD and ME. Straw quality traits were investigated at harvest and after three months of storage using farmer storage procedures. As in the preceding two papers on dual-purpose rice the observed cultivar-dependent variations were substantial with GY varying 1.8-fold, SY by a factor of 2.3 and HI by a factor of 1.6. Important straw fodder quality traits such straw N varied 1.5-fold and the cultivar with the highest IVOMD differed from the lowest one by 6.1% units. Though significant GxE effects were observed, h^2

were substantial (> 0.73) for SY and IVOMD and intermediate (>0.49) for GY, NDF, ADF and ME but poor (<0.17) for silica, N and ADL. To summarize, considerable cultivar-dependent variation in food and fodder traits exists among released cultivars, though key positive straw quality traits tend to be inversely ($P < 0.10$) associated with GY. Straw storage influenced straw quality, though in an unexpected way since positive straw quality traits increased while negative traits – except for ADL – decreased. Straw quality traits at harvest and after storage were still significantly correlated but the correlation coefficients (r) were generally substantially below 1. For example, the r for comparing rice straw at harvest and after storage was 0.82 for N, 0.72 for NDF and 0.57 for IVOMD. The comparatively low r for IVOMD suggests that changes in ranking of straw for this trait could occur during storage. More research is required including larger sets of cultivars to understand the mechanism, for example changes in straw morphology. Equivalent changes in ground and stored laboratory straw samples, for example in closed sample bags or cups, seem to be insignificant.

Chenfei Dong et al. in their study "*Rapid evaluation method for rice (*Oryza sativa* L.) straw feeding quality*" (this volume) investigated the potential of a rapid evaluation method for estimating rice straw fodder quality, reasoning that this would be a pre-condition for including rice straw fodder quality traits in rice improvement. Besides using routine laboratory quality traits such as crude protein (CP), ADF and *in vitro* dry matter digestibility (IVDMD) the authors analyzed nonstructural carbohydrates (NSC) as the sum of starch and water-soluble carbohydrates in whole rice straw and rice straw fractions. The top 3rd node of the rice straw stem was found to be the main NSC storage organ, and its starch content was positively ($P < 0.01$) correlated with IVDMD (between cultivar range of 5.5% units) and negatively ($P < 0.01$) with ADF. Unfortunately, the authors did not report correlation coefficients for these relationships. The fresh top 3rd inter-nodes of stem were used to make freehand sections and the starch particle quantity estimates in the parenchyma area of the top 3rd inter-node was consistent with the starch content in this part. Though ultimately a qualitative

estimate, the authors proposed that the starch particle quantity in the top 3rd inter-node of stem by free hand sections could be a rapid evaluation method for rice straw feeding quality.

To summarize, in rice straw, key laboratory fodder quality traits like IVOMD differed between cultivars by about 5 to 10% units. In rice and wheat straw trading (Duncan et al.) the difference in average IVOMD of rice and wheat straw of 6.3% units (rice straw 40% and wheat straw 46.3%) was associated with a price difference of around 19 %. These observations would suggest a price premium of about 3% per unit IVOMD. These premiums very broadly agree with findings reported for sorghum stover derived from ex-ante assessments (Kristjanson and Zerbin, 1999) and sorghum fodder market studies (Blümmel and Rao, 2006), where within-species price premiums of about 5% per unit IVOMD were observed for stover from different cultivars. These differences (ie of variation in IVOMDs from 47 to 52% were also associated with variation in milk potential of 5 kg per day (15 kg vs 10 kg) in dairy buffalo fed total mixed rations consisting of about 50% of sorghum stover (Blümmel et al. 2020). These increases in livestock performance have 2 components: higher IVOMD and higher feed intake; the latter as a response to the former. In other words, the impact of 5 to 10% units differences in IVOMD in rice straw on livestock productivity will very likely be substantial.

Findings on dual purpose wheat

Wheat is a major crop in temperate regions, including much of south Asia with less produced in sub-Saharan Africa. Wheat straw is used globally as a livestock feed resource. While it is of relatively low quality, opportunity may exist for improvement through crop breeding efforts. As mentioned previously in the paper by Duncan et al., wheat straw in India was of higher quality than rice straw and traded at higher prices.

In their paper "*Comparative assessment of food-fodder traits in a wide range of wheat germplasm for diverse biophysical target domains in South Asia*" (this volume) Blümmel et al. undertook a comprehensive analysis of wheat straw traits from a series of multi-location trials across India,

Bangladesh, Nepal and Pakistan and involving 6 distinct cultivar types suited to different agro-ecologies from CIMMYT's most recent wheat lines. Results indicated considerable variation in wheat straw traits between cultivar types especially for grain yield and straw yield. Correlations between grain yield and straw traits are important in terms of balancing breeding objectives for human food and livestock feed. In this study there was a negative correlation between grain yield and straw yield probably associated with the shorter stem length in modern varieties. However, the extent of reduction in straw yield explained by grain yield was a modest 14%. Examining relationships between grain yield and straw quality the general pattern was that these were negatively correlated. Turning to variation within cultivar types, grain yield and straw yield were unrelated in most cases. Straw N concentration was generally negatively associated with grain yield for most cultivars but unrelated to straw yield in all but one case. Similarly, straw digestibility was negatively associated with grain yield in 2 cultivar types but unrelated in the remaining four. The data emerging from this study show much less variation in straw quality parameters than studies with older cultivars suggesting that breeding has reduced overall genetic variation between wheat lines. There is thus less potential for selecting cultivars with positive livestock feed quality traits from the overall population than there was for older lines or indeed for other species such as maize, sorghum and pearl millet. However, the authors caution that further analysis is required to fully understand the relatively low genetic variation in wheat straw quality traits in these cultivar types and its implications for selection and breeding of wheat straw cultivars for livestock feeding objectives.

In their paper "*Variations in food-fodder traits of bread wheat cultivars released for the Ethiopian highlands*" Bezabih et al. (this volume) explored grain and straw yield and quality traits across several bread wheat varieties this time in Ethiopia. As the authors pointed out, wheat straw is an important source of livestock feed in Ethiopia and wheat accounts for the second highest area of cultivation in Sub-Saharan Africa. Despite the importance of wheat as a crop and as a source of livestock feed in Ethiopia, studies on genetic variation in wheat straw yield and quality are scarce. In

this study 25 released varieties were tested across 2 locations. A further study focused on five promising varieties across four locations representing considerable agro-ecological variation. Grain and straw yields showed considerable inter-varietal variation while variation in straw quality traits was much less evident. In the main 2-location study, grain and straw yield were positively correlated. For the most part, grain yield and straw quality traits (NDF, ADF, ADL, ME, IVOMD) showed no correlation with the notable exception of straw N concentrations which showed negative correlations with grain yield. The authors attribute this effect to the fact that the wheat lines have been bred for bread flour and that grain N concentrations are an important determinant of bread grain quality. Negative associations between grain yield and straw N concentration in straw and stover have been more often reported than negative associations between grain yields and IVOMD (Blümmel et al. 2020). Bezabih et al. provided a rationale for this, establishing an N balance from soil N, N fertilizer application and N recovery in wheat grain and straws and demonstrated that N supply limitations can impose inverse relationships between N sinks in grain and straw. Breeding simultaneously for grain yield and straw N concentration given the dual importance of grain yield and straw quality in the Ethiopian context will need to take note of this.

In the preceding papers the focus was on detecting variations in wheat straw quality in existing cultivars with the intention of exploiting these variations immediately, should trade-off analysis support it. The focus in the paper of Joshi et al in "*Variations in straw fodder quality and grain-straw relationships in a mapping population of 294 diverse spring wheat lines*" (this volume) was more strategic by exploring opportunities for further targeted genetic enhancement towards dual-purpose traits, Joshi et al. conducted an analysis of 287 wheat straw lines from a wheat association mapping population with a view to quantifying variation in straw and grain yield and straw quality traits. A further aim was to identify quantitative trait loci for key traits using a genome-wide association study (GWAS) using single nucleotide polymorphisms. A three-location trial in India was conducted along with a 3-year multi-season study in one location. Results indicated considerable

variation in straw and grain yields (around 2-fold) in the study population but relative minor variation in straw quality traits (30% variation at most). Variation was much less than in previous similar studies with maize lines. There was a significant positive association between grain and straw yield. Some of the straw quality traits (N, IVOMD, ME) showed significant but minor negative associations with straw yield while the remaining straw quality traits (NDF, ADF, ADL) showed weak positive associations with straw yield. The relatively weak nature of all these associations suggests that selection for straw quality traits would not interfere to any great extent with improvement of grain and straw yield in wheat. The GWAS identified markers for all six straw quality traits across five genomic regions. These markers were in most cases associated with relative minor phenotypic variation. This was partly related to the relatively minor overall variation in straw quality traits across this generally uniform population. Further studies with more diverse populations are needed to assess whether such markers would have value as indirect selection criteria for important quality traits.

Similarly in the study "*Opportunities for wheat cultivars with superior straw quality traits targeting the semi-arid tropics*" Joshi et al (this volume) tested variation in 50 wheat cultivars this time focusing on breeding lines targeting semi-arid conditions. A three-location trial was conducted over two years in India and Bangladesh involving 50 wheat lines. The results of the study generally agree with the similar study by Joshi et al. summarized above and that of Bezabih et al. in Ethiopia. The main findings were that genetic variation was mainly seen at the level of grain and straw yield and that variation in wheat straw quality was relatively minor in comparison. The study presents a series of relationships between grain yield and straw quality traits which each show the absence of discernible associations indicating that breeding for straw quality traits would not necessarily impede efforts to increase grain yield. The study also pointed to the very strong location and seasonal effects on grain and straw yield indicating the need to focus on agronomic improvements in efforts to maximize grain and straw yields.

In summary, these studies on wheat lines generally show that there is significant between-cultivar variation in straw yield although this variation is less marked than in other species such as maize and sorghum. This existing variation would allow selection of cultivars with favourable livestock feed characteristics from existing populations. Variation for quality traits in straw is moderate and again, less than for other species. In terms of breeding objectives, the relationships between grain yield and straw traits are important since improving straw traits at the expense of grain yield is undesirable. The broad finding of this set of studies is that there are weak negative relationships between grain and straw yields meaning that breeding for straw traits would need to take account of effects on grain yields. Bread wheat presents a special case in terms of N allocation within the plant since N concentrations in grain are an important determinant of quality and hence price. However, straw N is also important for livestock feed quality and hence some compromise could be required in terms of breeding for human food and livestock feed in bread wheat varieties.

Agronomic management of rice and wheat to increase fodder availability

Dual-purpose management of cereals holds promise to reduce the feed gap and to better integrate crop and livestock systems where seasonal forage deficits occur. Research on the agronomic management of wheat to increase fodder availability has focused on sowing time and cutting regimes including crop growth stage and cutting frequency (Bisht et al., 2008, 2012; Tian et al., 2012) prior to research on grazing management. In the study "*Bio-economic analysis of dual-purpose management of winter cereals in high and low input production systems*" conducted in the Central Anatolian plateau of Turkey, Atesa et al. (this volume) investigated the effect of spring defoliation at tillering and stem elongation under low- and high-input management on yield and quality of forage, straw and grain of barley, wheat and triticale during 2013-2015. Overall, barley had greater forage dry matter accumulation and straw yield under the favorable winter-spring season, relative to wheat and triticale but there was no difference under dry conditions. The wheat variety Dagdas 94

outperformed other wheat varieties for a number of traits . Total crude protein was greater in the systems with cut forages compared to the no-cut forages while grain yield was lower when cut at stem elongation stage for both years and management systems. Bioeconomic modelling indicated that growing cereals only for grain led to higher profits when the precipitation was lower than average, while dual-purpose management based on defoliation at tillering led to higher profits during an average year. Also cultivation of barley led to higher profits in all periods. In another study Mondal et al. (this volume) investigated *“Biomass yield and nutrient content of dual purpose wheat in the fruit based cropping system in the North-Western mid-Himalaya ecosystem, India”*. The wheat cultivar VL Gehun 829 provided good yields of grain (2.3 to 4.2 t ha⁻¹), nutritious green fodder (2.63 to 3.77 t ha⁻¹) as well as dry fodder (4.80 to 7.88 t ha⁻¹) for livestock, improving the livelihoods of hill farmers. Both studies confirmed the potential of dual purpose wheat as a valuable fodder resource in crop-livestock systems.

Recent research has sought to develop crop- and grazing-management strategies for dual-purpose crops in other countries (Pitta et al., 2011; Dove and Kirkegaard, 2014). Grazing of winter wheat is a significant beef cattle production strategy in the Southern and Central Plains of the U.S. (Lollata et al., 2017). Aspects examined have included grazing effects on crop growth, recovery and yield along with an understanding of the grazing value of the fodder, its implications for animal nutrition and grazing management to maximise live-weight gain. Understanding grazing initiation, intensity, and termination are crucial in determining wheat's recovery potential and ability to produce grain following grazing. By alleviating the winter 'feed gap', the increase in winter stocking rate afforded by grazing crops allows crop and livestock production to be increased simultaneously on the same farm. Sprague et al. in the paper *“Dual-purpose cereals offer increased productivity across diverse regions of Australia's high rainfall zone”* (this volume) investigated the productive value of dual-purpose cereals – wheat, barley and triticale - across diverse regions of Australia's high rainfall zone through the use of different management packages. In each zone, specific grazing regimes such as

length of grazing period and “the safe phenological window” were identified with respect to climatic variation. Overall, the experiments confirm the predicted potential for dual-purpose production of cereals across the Australian high rainfall region provided appropriate cultivar and sowing dates are combined with careful grazing management. Further work is required to refine grazing management to reduce reductions in grain yield in well-managed dual-purpose crops grazed prior to stem elongation in the above environments.

Unlike wheat, dual-purpose rice for forage is managed as a ratoon crop after the grain has been harvested. In southern China, ratoon rice is able to produce a reasonable grain yield however, in eastern China and other subtropical and temperate rice planting areas, water requirements and high temperatures cannot support the growth period of ratoon rice for grain, but supports the vegetative growth to produce feed. In their paper “*Developing Ratoon rice as forage in subtropical and temperate areas*” Chenfei Dong et al. (this volume) investigated ratooning rice varieties to increase forage yield in subtropical and temperate rice planting areas. Of fourteen Indica varieties, Zhunliangyou 608 showed significantly higher regeneration rate, regrowth tiller height, and dry matter yield than other varieties. In studies of cutting height, cutting days after grain harvest and gibberellic acid (GA) treatment, the best overall treatment for rice feeding quality (in vitro dry matter digestibility and nonstructural carbohydrates) of Zhunlianyou 608 was 30 cm stubble height for the first season, applying GA on the 6th day and cutting on the 37th day after first harvest with 5 cm cutting height. Ratooned rice therefore has a role to increase forage availability during the gap period after rice grain is harvested and before wheat is sown. As in similar research in Japan that focused on the effect of cultivar selection, cutting height and planting time on dry matter yield and nutrient content of forage (Nakano et al., 2007, 2008), Chenfei Dong et al. proposed the use of ratooned rice to prepare silages.

In summary, the findings from the agronomic studies on both dual-purpose wheat and rice provide a convincing case for their inclusion in crop-livestock systems to improve the availability of high-quality forage for improved efficiency and profitability in such systems. In comparison to dual-purpose wheat where lessons learned from agronomic studies have been successfully developed into viable grazing management regimes in several countries (e.g. USA and Australia), more research is needed on the role of dual-purpose rice in animal production systems.

Conclusions

From the afore-mentioned work with sorghum, pearl millet, maize, groundnut and cowpea two approaches emerged to provide cultivars with superior grain yield and straw fodder traits. First, to simply phenotype existing cultivars for variation in straw fodder traits to detect existing and exploitable variations. This approach is quick and requires moderate investment. Second, targeted genetic enhancement towards better straw fodder quality traits using conventional or molecular breeding methodologies. This approach is longer term and requires higher investments than needed for simple phenotyping for immediately exploitable variations. The findings in this special issue suggest that the first approach is promising for rice while in wheat, cultivars superior for grain and straw traits might need targeted genetic enhancement.

For both approaches suitable infrastructure for phenotyping has been established by ILRI and crop science partners in the form of Near Infrared Spectroscopy (NIRS) hubs in Asia and Africa. NIRS was used in most of the papers in this special issue (see specifically Subudhi et al.) This non-destructive technique is much quicker and much more affordable than wet chemistry and *in vitro* analysis though still requires the harvesting, drying, grinding and transport of samples. Pocket-sized mobile NIRS that are becoming increasingly available could overcome these constraints by facilitating measurements in standing crops in the field (Prasad et al., 2019), which would reduce the investment costs for both approaches and providing faster input data for the second approach.

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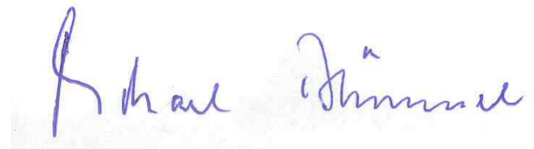
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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

A handwritten signature in blue ink, appearing to read "Rohan Kumar". The signature is written in a cursive style with a small 'n' above the 'm' in "Kumar".

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