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Extractable soil nutrient effects on feed quality traits of crop residues in the semiarid rainfed mixed crop–livestock farming systems of Southern India

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Abstract In the mixed crop–livestock systems, while general relation among feed quality, productivity and soil nutrient management have been reported, information on the effects of extractable soil nutrients on crop residue (CR) feed quality traits is scarce (e.g. in semiarid regions of Karnataka, India). In view of the increasingly important role of CR as feed components, in these farming systems, generating such information is a relevant research issue for sustainable development. Here, we report the occurrence and strength of relationships among extractable nutrients in soils and CR feed quality traits, and the effects of improved nutrients input on feed availability and feed quality of CR. Soil samples were collected from farmers' fields in the semiarid zone of Karnataka and analyzed for available phosphorus (P), potassium (K), sulphur (S), zinc (Zn) and boron (B) using standard laboratory methods. Soil test results were clustered as low, medium or high based on the level of nutrient concentration. Four major farming systems involving nine crops and 419 farms were selected for on-farm trials. Under every sample farm, a plot with farmer's practice (control) and improved fertilizer inputs (combined application of nutrients found deficient by soil testing) were laid. Performance of crops was recorded. Samples were collected for

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CR feed quality trait analysis using Near Infrared Reflectance Spectroscopy. The result showed that for cereal and oil crops, extractable soil S was significantly negatively associated with anti-feed quality traits such as neutral detergent fibre (NDF), acid detergent fibre (ADF), acid detergent lignin (ADL) ($P < 0.01$), but significantly positively related to metabolizable energy (ME) and in vitro digestibility ($P < 0.01$). Extractable B and K levels were associated positively and significantly with NDF, ADF and ADL for oil crops and cereals. Crop level associations, for most crops, showed similar trend. Improved fertilizer inputs affected CR yield much more than it did the quality. It increased ME productivity (ME ha^{-1}) and thereof the potential milk yield ha^{-1} by as high as 40 % over the control. Therefore, balanced nutrient inputs on crop land positively impact productivity of the livestock compartment of mixed crop–livestock farming system, and this knowledge can build on the currently perceived need and benefits of balanced nutrient replenishment in crop–livestock system.

Keywords Improved soil nutrients input · Sustainable development · Feed quality factors · Feed productivity

1 Introduction

Rainfed agriculture covers 80 % of the world cropland and produces more than 60 % of cereal grain (Rockström and Barron 2007). In India, rainfed agriculture has a distinct place and occupies 67 % of the cultivated area, contributing 44 % of the food grains and supporting 40 % of the human and 65 % of the livestock population (Singh et al. 2000). Rainfed agriculture is of critical importance for the livelihood of smallholder farmers in the arid and semiarid region of southern India (e.g. Karnataka). In these regions, livestock are strongly associated with crop production. For example, Ramachandra et al. (2000) reported that crop residues (CR) constitute >50 % of the livestock feed components, while livestock serve as an important source of inputs (e.g. manure) and also provide major traction serves to crop production practices. Although feeding on CR is considered a promising strategy to enhance resource use efficiency in crop–livestock farming system, as sustainable agricultural intensification is gaining a momentum, there are growing concerns regarding CR's feed quality (e.g. Blümmel et al. 2009a, b), availability (Haileslassie et al. 2011a, b; Ramachandra et al. 2004) and the possible tradeoffs with soil fertility management and conservation agriculture. Here, conservation agriculture is defined as minimal soil disturbance (no-till) and permanent soil cover (mulch from CR) combined with rotations, as a more sustainable farming system for the future.

Emerging evidence suggests that years of cultivation and imbalanced nutrient inputs depleted soil nutrient stocks in the mixed crop–livestock farming systems in the semiarid region (Rajashekhara Rao et al. 2010). For example, deficiencies of nitrogen (N) (in 31–81 % of farm fields), phosphorus (P) (in 31–67 % of farm fields), sulphur (S) (in 79–93 % of farm fields), boron (B) (in 39–91 % of farm fields) and zinc (Zn) (in 32–80 % of farm fields) across six districts in Karnataka are reported (Sahrawat et al. 2007, 2011). Probably, the fact that advocating sufficient fertilizer input to crop land did not involve benefits from CR and animal productivity might have also stagnated perceived importance of balanced nutrient management.

As a result of widespread deficiencies of major, secondary and micronutrients coupled with water shortage, crop yield gap in semiarid regions is wide. An assessment undertaken by Singh et al. (2011), for example, revealed nutrient limited yield gap of 35–58 % for various crops [finger millet (*Eleusine coracana* (L.) Gaertn, groundnut (*Arachis hypogaea* (L.), maize (Zea *mays* (L.), soybean (*Glycine max* (L.) Merr]. Here, we argue that the effects of such dwindling ecosystems' production services provision (e.g. soil nutrient and associated crop yield) on livestock are manifold: (1) low feed availability because of low biomass productivity; (2) low feed quality associated with multi-nutrient deficiencies (Gowda et al. 2004). Blümmel et al. (2009b) also suggested that as a compensation for low feed quality, livestock's total dry matter demand can be higher, and this puts additional pressure on the already feed-deficit farming systems and thus hampers efforts made by the international and local communities to take advantage of the development opportunity offered by the global 'livestock revolution' [e.g. increasing demand for livestock products (Steinfeld et al. 2006)]. Then, the question is as to how soil nutrient inputs-based interventions, addressing these yield gaps, affect the soil–crop–livestock interface?

This study presents a detailed analysis of linkage between balanced soil nutrient management and CR feed quantity and quality, using data from on-farm experiments. It involves fertilizer input, soil and biomass sampling, analysis and linking it to efficiency of feed Metabolizable Energy (ME) utilization. The main objectives were: (1) to illustrate the occurrence and strength of the relationships among extractable or available soil nutrients (N, P, K, S, B and Zn) and CR feed quality traits and (2) to evaluate the effects of nutrients input on feed availability, feed quality traits and associated livestock products (e.g. potential milk yield) in rainfed mixed crop–livestock farming systems of the semiarid regions.

2 Materials and methods

2.1 Study region and site selection

This study was undertaken in the rainfed mixed crop–livestock farming systems of the semiarid region of Karnataka, India. Ramachandra et al. (2004) classifies Karnataka into three major regions: the arid, semiarid and coastal regions. We focused on the semiarid region as it covers a significant area of the state and represents important features of rainfed crop–livestock farming systems of Southern Asia (Rajashekhara Rao et al. 2010; Ramachandra et al. 2004).

Multi-stage stratified random sampling method (Sahrawat et al. 2005) was used to select seven sample districts (Fig. 1), 31 taluks or blocks,[1] 129 villages and 419 farms. Representativeness of the mosaic of landscape, cropping systems and soil types were among the criteria used to select the study districts. First, districts representing the different sub-farming systems of semiarid regions (hot dry semiarid; hot moist semiarid and hot dry sub-humid) were selected (Table 1). Secondly, within each district, taluks and villages representing the different farming systems were randomly selected. Depending on the major crop areas coverage (2008/2009 cropping season), the study districts can be clustered as: (1) sorghum-based pulses; (2) pulses-based oil crop; (3) maize-based sorghum; and (4) millet-based oil crop farming systems (Table 1).

[1] Taluk or block is the second lowest administrative unit in India.

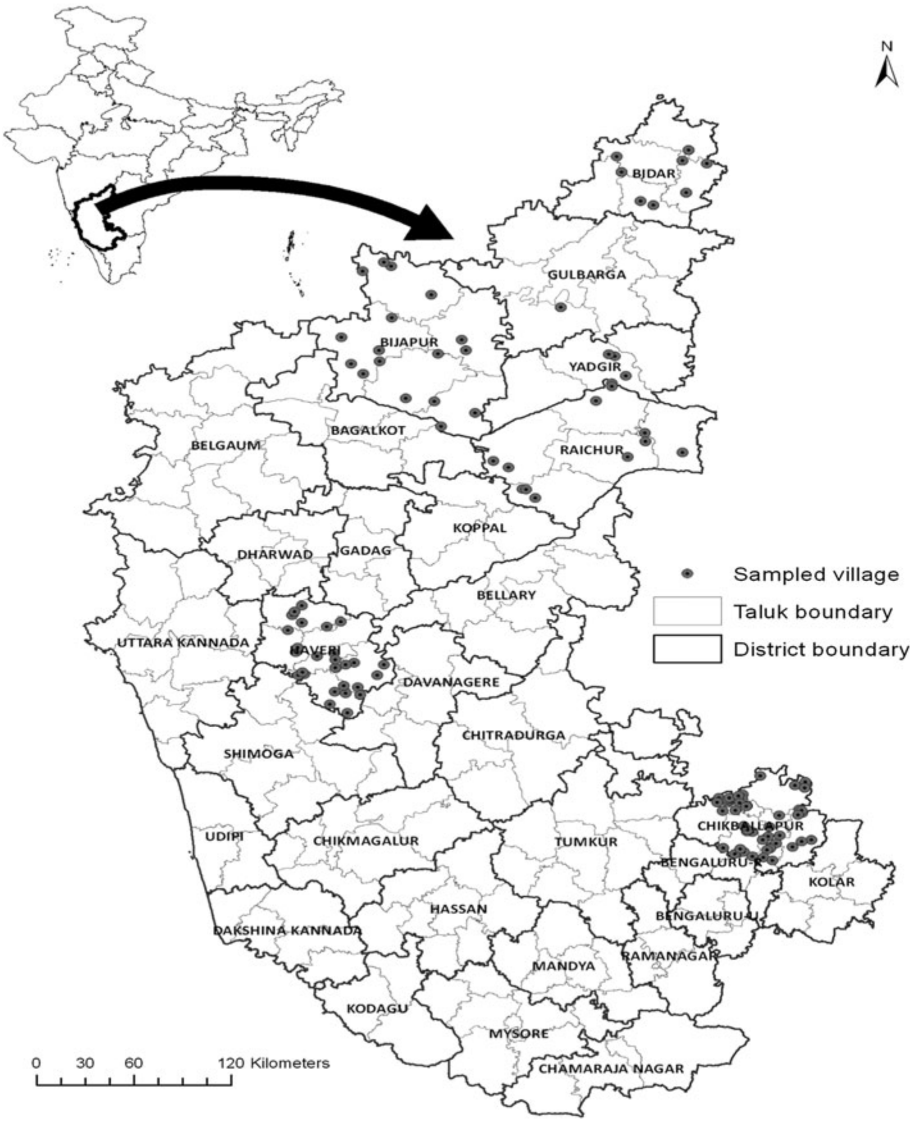

Fig. 1 Location of sample districts, taluks and villages (note that all sampled village could not be indicated on the map because of the scale's limitation)

2.2 Characterization of farming systems

Livelihoods in the study farming systems are mainly based on crop and livestock production: >70 % of the population are involved in agriculture and related practices (Purushothaman and Kashyap 2010). Ministry of Water Resources, Government of Karnataka, Central Ground Water Board [CGWB (2008)] reported that 70–90 % of the total area under crop is rainfed, and the southwest monsoon contributes 55–85 % of the annual rainfall. Crops such as finger millet (*Eleusine coracana* (L.) Gaertn, sorghum

Table 1 Salient features of the districts studied in the semiarid eco-region of Karnataka, India

Characteristics	Study districts						
Regions	Bidar Hot moist semiarid	Gulbarga Hot moist semiarid	Yadagir Hot moist semiarid	Raichur Hot dry semiarid	Bijapur Hot dry semiarid	Haveri Hot dry sub-humid	Chickballapur Hot moist semiarid
Rain fall (mm $year^{-1}$)	827	719	719	578	582	790	862
Temperature (°C)	20–42	13–30	13–30	18–40	20–42	18–40	18–45
Farming system (major crop production %)	Sr (28) Pp (21) Cp(20)	Cp (60) Sf (28) Sr (25)	Pp + Sr + Sf	Sr (26) Sf (22) Ri (19)	Sr (33) Pl (12)Sf (22)	Mz (28) Sr (20) Ct (18)	Fm + Gn
Livestock herd composition (%)	Bf (36), In (54)Cb (3) Sm (7)	Bf (19) In (67) Cb (1) Sm (13)	ND	Bf (29) In (53) Cb(2) Sr (16)	Bf (43) In (42) Cb (0) Sm (15)	Bf (26) In (55) (Cb 7) Sm (11)	Bf (10) In (46) Cb (30) Sm (13)
Ratio of total available feed ME to SLU (GJ SLU^{-1} $year^{-1}$	19.63	15.81	ND	13.79	21.67	9.86	ND
Share of the different feed components (%)	Cr (73) Con(3) Gre (25)	Cr (67) Con (6) Gre (27)	ND	Cr (63) Con(8) Gre (29)	Cr (64) Con (6) Gre (30)	Cr (52) Con (7) Gre (41)	ND

Sb soybean, *Cp* chick pea, *Sr* sorghum, *Pp* pigeon pea, *Ri* for rice, *Gn* ground nut, *Sf* sunflower, *Mz* maize, *Fm* finger millet, *Bf* buffalo, *In* indigenous cattle, *Cb* cross breed cattle, *Sm* small ruminant, *ME* metabolisable energy, *SLU* standard livestock unit (equivalent to 350 kg lives weight), *Cr* crop residues, *Con* concentrates, *Gre* green fodder, *ND* no data

(*Sorghum bicolor* (L.) Moench, rice (*Oryza sativa* (L.), chickpea (*Cicer arietinum* (L.), groundnut (*Arachis hypogaea* (L.), maize (Zea *mays* (L.), sunflower (*Helianthus annuus* (L.), sugarcane (*Saccharum officinarum* (L.) and soybean (*Glycine max* (L.) Merr are important (CGWB 2008; Purushothaman and Kashyap 2010; Ramachandra et al. 2004).

Farmers in the study areas are also raising different livestock species and breeds. Cattle [(*Bos indicus)* and *(Bos taurus taurus*)], sheep (*Ovis aries*), goat (*Capra hircus*) and buffalo (*Bubalus bubalis*) are important livestock species [Ministry of Agriculture, Government of India (MoAGI) 2010]. There is livestock management disparity between the studied farming systems: in terms of herd composition and level of intensification (Table 1). For example, finger-millet-based oil crop farming system of hot moist semiarid region (Table 1) has more than 30 % exotic and cross breed animals, while the sorghum-based chickpea farming system of hot dry semiarid region has >95 % indigenous breed (MoAGI 2010). Access to market and feed availability are often reported as the major driver of these variations. In all districts, milk production is one of the major objectives of livestock management (MoAGI 2010).

The crop–livestock association is generally reported as strong (e.g. Ramachandra et al. 2000), but local variation exists, depending on the types of crops, their productivity and nutritive value and availability of other feed sources [such as grazing on common property resources (Table 1)]. In the entire studied farming systems, CR constitute between 52 and 73 % of the feed ingredient (Table 1), and the ratio of available ME to SLU[2] [Standard Livestock Unit)] ranges between 9,000 and 21,000 MJ SLU^{-1} $year^{-1}$. If we assume 67 MJ of ME SLU^{-1} day^{-1}, annual ME requirement for a typical mixed herd structure[3] will be 24,693 MJ SLU^{-1}, suggesting an enormous magnitude of variation in feed demand and supply (Table 1)]. In the scenario of no feed sourcing from adjacent areas, farming systems with low ME to SLU ratio suffer from feed deficit (compare also Parthasarathy Rao and Hall 2003).

2.3 Data collection and experimentation

2.3.1 Soil sampling and analysis

Before conducting the on-farm experiments, soil samples were collected (December 2009) from 20 % of villages in 31 taluks. Core samples (8–10 undisturbed samples), from 0 to 15 cm soil depth, representing different land units in different landscape positions (upper, middle and bottom parts of the topo-sequence), were randomly collected and composited (Sahrawat et al. 2008). Soil parameters such as pH, organic carbon (OC, as a proxy for available N), available phosphorus (P), sulphur (S), potassium (K), boron (B) and zinc (Zn) were analyzed.

The composite soil samples were homogenized, air dried and powdered with a wooded hammer to pass through a 2-mm sieve before analyses. Soil analysis was carried out in the Central Analytical Service Laboratory of the International Crop Research Institute for Semiarid Tropics [ICRISAT, Patancheru, India (Sahrawat et al. 2008; Rajashekhara Rao et al. 2010)]. Soil OC was determined using the modified Walkley–Black method (Nelson and Sommers 1996). Available P was extracted by sodium bicarbonate solution (Olsen and Sommer 1982) and extractable S was estimated by using 0.15 % calcium chloride as

[2] One SLU is equivalent to 350 kg animal live weight.

[3] Typical mixed herd structure means herd structure of different age, production level and species composition. Estimate was based on 2007 livestock census for India (MoAGI 2010) at district level.

extractant (Sahrawat et al. 2002, 2010). Extractable K was determined with ammonium acetate, Zn by diethylenetriaminepentaacetic (DTPA) reagent and available B was extracted by hot water method as described earlier (Kern 1996; Sahrawat et al. 2010). Soil pH was measured by a glass electrode using a soil to water ratio of 1:2. Electrical conductivity (EC) was measured by EC meter using soil to water ratio of 1:2.

To facilitate nutrient inputs for on-farm trials, the soil nutrient concentrations were clustered as low, medium and high (Rajashekhara Rao et al. 2010; Sahrawat et al. 2007). The results were extrapolated to the whole villages using a Geographic Information System (GIS)-based inverse distance weighting methods, so that villages and farms not sampled for soil analysis but sampled for crop were represented in the soil data.

2.3.2 Participatory on-farm experiments and recording of crop performance

In 2009/2010 cropping season, field experiments were conducted on 838 plots of 419 farms. This was a participatory on-farm experiments conducted on farmers' fields following standard agronomic practices. This was a participatory on-farm experiment: in essences that the experiment was conducted on farmers field, and day to day agronomic practices were undertaken by the farmers with a closer supervision by ICRISAT field staff. The Universities of Agricultural Science of Dharwad and Bangalore provide Zonal[4] level (but crop specific) fertilizer input recommendation of major nutrients across the different farming systems in the semiarid region of Karnataka. Information from the Karnataka state Agriculture Office indicates that farmers are widely practicing this recommendation in addition to the organic fertilizer inputs and associated agronomic practices (e.g. cropping pattern). These farmers' practices of nutrient input to crops, involving sorghum, millet, maize, chickpea, ground nut, pigeon pea, soybean and sunflower, were considered as a control experiment.

The treatment involved disaggregation of these Zonal level fertilizer recommendations to village level (based on soil nutrient status gradient) and micro nutrients added, those that are widely reported to be deficient in these semiarid regions (e.g. Sahrawat et al. 2008; Sahrawat et al. 2010 and Rajashekhara Rao et al. 2010). In farmers' fields, where N, P and K deficiency exceeded 50 % of the sampled farms fields, full N, P and K doses (as suggested by Karnataka States Ministry of Agriculture) plus 200 kg ha^{-1} of gypsum, 25 kg ha^{-1} of zinc sulphate ($ZnSO_4$) and 5 kg ha^{-1} of borax were applied in the balanced nutrient treatment. In fields, where nutrient deficiency was less than 50 % of the sampled farms fields, half of the recommended doses of N, P and K plus $ZnSO_4$, gypsum and borax (as above) were applied. Performances of crops, for grain and biomass yield, were recorded from 9 m^2 plots, and 838 samples of residue (treatment + control) were collected for feed quality trait analysis.

2.3.3 Plant sampling and analysis for feed quality traits

Collected residues samples were sundried and ground at the ICRISAT (Patancharu) for feed quality traits analysis including dry matter (DM), organic matter digestibility (OMD), crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF) and metabolizable energy (ME), ash, in vitro organic matter digestibility (IVODM)). For these analyses, the Near Infrared Reflectance Spectroscopy (NIRS) facility at the Nutritional Laboratory of the International Livestock Research Institute (ILRI) was used as described by Bidinger and Blümmel (2007) and Blümmel et al. (2007).

[4] Zone consists of as many as 10 Districts.

2.4 Data analysis

The relationships among extractable soil nutrients and CR feed quality traits, under farmers' practices, were established (using Pearson correlation), and the variation in CR feed quality traits across the extractable soil nutrients gradients was analyzed (for crop group and individual crop) using Analysis of Variance (ANOVA). The effects of balanced nutrient management practices on CR feed quality and quantity were analyzed by comparing values of control *vis a vis* treatment. Also, we examined the effects of treatment on ME productivity (MJ ha^{-1} $year^{-1}$) and its efficiency of utilization for milk production, resulting in gross potential financial benefit for smallholder farmers in different farming systems of the study area. The following assumptions and equations were applied in computing these relationships:

1. Requirement of energy for milk production was calculated as a function of weight of milk (kg) and its Energy Value (EV1), whereas EV1 was calculated using Eq. 1 (McDonald et al. 1988)

$$\mathrm{EV1} = 0.0386\mathrm{BF} + 0.0205\mathrm{SNF} - 0.236 \quad (1)$$

where EV1 is milk energy value (in MJ kg^{-1}), BF is Butter Fat content (g kg^{-1}) assumed 50 % for buffalo and 35 % for cow and average values, weighted by buffalo–cow population in every study farming system. Solid Not Fat Content (SNF) of milk (g kg^{-1}) assumed 90 for buffalo and 85 for cow and at farming system scale average values, weighted by buffalo–cow population in every study farming system, was used.

2. The efficiency of utilization of ME for milk production (Kl) was estimated at farming system scale by Eq. 2 (McDonald et al. 1988)

$$\mathrm{Kl} = 0.3qm + 0.420 \quad (2)$$

where Kl is efficiency of utilization of ME and *qm* is metabilizability factor calculated as a function of ME concentration in CR produced under control and treatment experiments.

3. To convert the ME values of CR from the treatment and control experiments to milk, the ME requirement for the production of a kg of milk was estimated from the ratio of Eqs. 1, 2 (McDonald et al. 1988).
4. ME productivity (MJ ha^{-1}) was estimated from ME concentration (MJ kg^{-1}) and stover dry matter yield (kg ha^{-1}) for the different study farming systems under treatment and control. To estimate gross potential benefits from improved efficiency of ME utilization and ME productivity, total ME (MJ ha^{-1}) was converted to milk (step iii) and financial value assuming uniform price of milk across the study farming systems.

3 Results

3.1 Extractable soil nutrients and their relationships with crop residues' feed quality traits

The results of soil analysis revealed that about 79 % of farmers' fields were deficient in organic carbon (OC). The next widespread deficient soil nutrient was S. About 74 % of farmers' fields showed deficiency. Deficiencies of extractable P, Zn and B were distinct

Table 2 Extractable soil nutrients gradient and distribution across sampled fields and crop groups in the semiarid region of Karnataka, India

Crop group	Extractable nutrients	Mean values of available nutrients (mg kg^{-1}) under different nutrient gradients			% of sampled fields under different soil nutrient gradients		
		Low	Medium	High	Low	Medium	High
Pulses (chickpea, pigeon pea)	OC (%)	0.40	0.57	0.82	71.70	25.47	2.83
	P (mg kg^{-1})	3.22	6.93	15.11	45.28	27.36	27.36
	K (mg kg^{-1})	NV	94.09	231.15	0.00	12.26	87.74
	S (mg kg^{-1})	5.32	32.95	NV	58.49	41.51	0.00
	B(mg kg^{-1})	0.33	0.68	1.55	5.66	77.36	16.98
	Zn (mg kg^{-1})	0.45	0.74	1.19	60.38	25.47	14.15
Oil crops (ground nut, soybean, sunflower)	OC (%)	0.37	0.74	0.82	94.87	2.56	2.56
	P (mg kg^{-1})	3.05	7.69	15.31	17.95	33.33	48.72
	K (mg kg^{-1})	43.81	87.04	234.69	7.69	69.23	23.08
	S (mg kg^{-1})	7.35	12.49	NV	79.49	20.51	0.00
	B(mg kg^{-1})	0.34	0.59	NV	64.10	35.90	0.00
	Zn (mg kg^{-1})	0.42	0.789	1.21	23.08	64.10	12.82
Cereals (sorghum, finger millet, maize)	OC (%)	0.43	0.56	0.82	73.26	25.00	1.74
	P (mg kg^{-1})	3.75	7.01	23.55	15.70	24.42	59.88
	K (mg kg^{-1})	47.94	94.60	178.11	1.74	40.12	58.14
	S (mg kg^{-1})	6.58	13.39	NV	80.81	19.19	0.00
	B (mg kg^{-1})	0.319	0.674	NV	15.70	84.30	0.00
	Zn (mg kg^{-1})	0.47	0.80	1.94	17.44	45.35	37.21

The values used for grouping the level of nutrient are: <0.5 % OC is low; 0.5–0.75 % medium and >0.75 % high; extractable P (Olsen method) <5 mg kg^{-1} is low, 5-10 mg kg^{-1} medium and >10 mg kg^{-1} high; extractable K < 50 mg kg^{-1} is low, 50–125 medium and >125 high; extractable Zn < 0.75 mg kg^{-1} low, 0.75–1.5 mg kg^{-1} medium and >1.5 mg kg^{-1} high; hot water extractable B < 0.58 is low; >0.58 high; $Cacl_2$ extractable S < 10 mg kg^{-1} is low and >10 mg kg^{-1} high; *NV* no value

when we disaggregate the observations into fields under different crop groups (Table 2). Fields used for pulses were the most deficient in P (45.28 % of the fields) and Zn (60.4 % of the fields), while B deficiency was observed on 64.10 % of fields used for oil crops. Extractable K was medium to high on 96 % of sample fields (Table 2).

The results in Table 3 show correlations among soil extractable nutrients and CR feed quality traits for different crop groups. Association of S with NDF, ADF and ADL was significant; and it was negative for cereals (Table 3) and oil crops (Table 3), whereas no significant relationship was observed for pulses (Table 3). Phosphorus showed similar trend for cereals, but showed no significant relationships with NDF, ADF and ADL for pulses and oil crops. Extractable Zn also showed a significant negative association with ADF and NDF for cereals.

Another distinct observation was the association of extractable K and B with feed quality traits: for cereals (Table 3), K and B tended to be inversely and significantly related with ME and IVODM, while their associations with NDF, ADF and ADL were positive and significant (at $P = 0.01$, Table 3). Crop level associations showed similar tendency as crop group, though the relationships were relatively weak.

Table 3 Correlation coefficients of extractable soil nutrients (under farmers' practices) with livestock feed quality traits for (a) cereals residues (b) oil crops, (c) pulse residues in semiarid region of Karnataka, India

Parameters	Nutrient concentration (mg kg^{-1})				CR feed quality traits (%-DM)						ME (MJ kg^{-1}
	P	K	S	B	Zn	CP	NDF	ADF	ADL	IVOMD	
(a) cereals residues[a]											
P	1										
K	−0.01	1									
S	0.33**	−0.27**	1								
B	−0.23**	0.25**	−0.35**	1							
Zn	0.94**	−0.05	0.34**	−0.13	1						
CP	0.04	−0.08	0.06	−0.03	0.05	1					
NDF	−0.34**	0.20**	−0.39**	0.42**	−0.31**	−0.51**	1				
ADF	−0.49**	0.42**	−0.43**	0.36**	−0.47**	−0.50**	0.69**	1			
ADL	−0.41**	0.54**	−0.50**	0.27**	−0.41**	−0.09	0.48**	0.76**	1		
IVODM	0.52**	−0.41**	0.48**	−0.28**	0.51**	0.08	−0.47**	−0.78**	−0.81**	1	
ME	0.46**	−0.41**	0.41**	−0.18*	0.45**	−0.10	−0.24**	−0.65**	−0.79**	0.95**	1
(b) oil crops[b]											
P	1										
K	−0.01	1									
S	0.35**	−0.27**	1								
B	−0.12	0.64**	−0.29**	1							
Zn	0.65**	−0.10	0.18*	0.04	1						
CP	0.10	−0.71**	0.26**	−0.58**	0.17*	1					
NDF	−0.10	0.64**	−0.27**	0.50**	0.02	−0.78**	1				
ADF	0.01	0.64**	−0.24**	0.52**	0.01	−0.78**	0.81**	1			
ADL	−0.09	0.45**	−0.21*	0.32**	0.05	−0.31**	0.60**	0.72**	1		
IVODM	0.04	−0.24**	0.08	−0.15*	0.03	0.11	−0.17*	−0.52**	−0.76**	1	
ME	−0.02	−0.00	0.00	0.03	−0.02	−0.18*	0.10	−0.28**	−0.62**	0.94**	1

Table 3 continued

Parameters	Nutrient concentration (mg kg^{-1})				CR feed quality traits (%-DM)						ME (MJ kg^{-1})
	P	K	S	B	Zn	CP	NDF	ADF	ADL	IVOMD	
(c) pulse residues[c]											
P	1										
K	0.27**	1									
S	0.23**	0.13	1								
B	0.23**	0.29**	0.61**	1							
Zn	0.53**	0.24**	0.23**	0.34**	1						
CP	−0.16*	−0.30**	−0.11	−0.02	−0.18*	1					
NDF	0.14	0.23**	0.02	−0.03	0.11	−0.96**	1				
ADF	0.12	0.25**	0.00	−0.07	0.11	−0.96**	0.97**	1			
ADL	0.08	0.22*	0.03	−0.12	0.10	−0.86**	0.86**	0.89**	1		
IVODM	−0.16*	−0.03	0.07	0.14	0.00	0.21*	−0.28**	−0.25**	−0.36**	1	
ME	−0.21*	0.03	0.04	0.07	−0.04	−0.19*	0.14	0.16*	0.02	0.87**	1

[a] $N = 157$; * $P < 0.05$; ** $P < 0.01$. *OC* organic carbon, *P* phosphorus, *K* potassium, *S* sulphur, *B* boron, *Zn* zinc, *CP* crude protein, *NDF* neutral detergent fibre, *ADF* acid detergent fibre, *ADL* acid detergent lignin, *IVODM* for in vitro organic matter digestibility, *ME* metabolisable energy, cereals residues include stalks and stubble (stems), leaves, and seed pods and does not include process residues

[b] $N = 132$

[c] $N = 132$

Table 4 Variation in cereals residues feed quality traits across extractable S, Zn, P, K and B gradients in mixed crop–livestock systems in the semiarid region of Karnataka, India (under farmers' practices)

Feed quality traits	Nutrient gradients	S		Zn		P		K		B	
		SN	Mean ± SD	SN	Mean ± SD	SN	Mean ± SD	SN	Mean ± SD	SN	Mean ± SD
CP (%-DM)	Low	127	7.34 ± 1.50^{a}	15	7.44 ± 1.72^{a}	15	7.44 ± 1.91^{a}	3	5.85 ± 0.56^{a}	27	7.41 ± 1.43^{a}
	Medium	30	7.53 ± 1.35^{a}	78	7.27 ± 1.42^{b}	39	7.13 ± 1.34^{a}	69	7.66 ± 1.52^{b}	130	7.37 ± 1.48^{a}
	High		NV	64	7.49 ± 1.48^{a}	103	7.46 ± 1.45^{a}	85	7.21 ± 1.39^{ab}		NV
NDF (%-DM)	Low	127	66.67 ± 5.92^{a}	15	67.22 ± 4.58^{a}	15	67.31 ± 4.58^{ab}	3	63.52 ± 1.70^{ab}	27	62.97 ± 5.29^{a}
	Medium	30	62.63 ± 3.84^{b}	78	68.31 ± 4.83^{a}	39	68.74 ± 4.75^{a}	69	64.12 ± 5.84^{b}	130	66.51 ± 5.73^{b}
	High		NV	64	62.65 ± 5.63^{b}	103	64.62 ± 5.92^{b}	85	67.43 ± 5.43^{a}		NV
ADF (%-DM)	Low	127	43.99 ± 3.62^{a}	15	43.81 ± 3.41^{a}	15	44.01 ± 3.55^{ab}	3	41.49 ± 2.02^{ab}	27	41.54 ± 3.35^{a}
	Medium	30	40.86 ± 2.39^{b}	78	45.05 ± 2.75^{a}	39	45.24 ± 2.59^{a}	69	42.40 ± 3.49^{b}	130	43.78 ± 3.58^{b}
	High		NV	64	41.28 ± 3.58^{b}	103	42.61 ± 3.74^{b}	85	44.27 ± 3.58^{a}		NV
ADL (%-DM)	Low	127	5.07 ± 0.93^{a}	15	5.17 ± 1.17^{a}	15	5.32 ± 1.11^{a}	3	4.19 ± 0.17^{ab}	27	4.48 ± 1.03^{a}
	Medium	30	$4.10 \pm .84^{b}$	78	5.24 ± 0.73^{a}	39	5.21 ± 0.92^{a}	69	4.61 ± 0.94^{b}	130	4.97 ± 0.96^{b}
	High		NV	64	4.39 ± 1.02^{b}	103	4.70 ± 0.95^{a}	85	5.14 ± 0.98^{a}		NV
IVODM (%-DM)	Low	127	52.63 ± 2.51^{a}	15	51.96 ± 2.87^{a}	15	52.13 ± 2.98^{a}	3	54.78 ± 1.58^{ab}	27	53.91 ± 2.98^{a}
	Medium	30	55.19 ± 2.58^{b}	78	51.93 ± 1.79^{a}	39	51.97 ± 2.32^{a}	69	53.64 ± 2.68^{b}	130	52.96 ± 2.63^{a}
	High		NV	64	54.85 ± 2.70^{b}	103	53.70 ± 2.65^{b}	85	52.64 ± 2.69^{a}		NV
ME (MJ kg^{-1})	Low	127	7.48 ± 0.44^{a}	15	7.35 ± 0.59^{a}	15	7.38 ± 0.61^{ab}	3	7.88 ± 0.31^{a}	27	7.66 ± 0.53^{a}
	Medium	30	7.87 ± 0.50^{b}	78	7.39 ± 0.36^{a}	39	7.42 ± 0.46^{c}	69	7.62 ± 0.48^{a}	130	7.54 ± 0.46^{a}
	High		NV	64	7.81 ± 0.47^{b}	103	7.64 ± 0.44^{b}	85	7.50 ± 0.47^{a}		NV

ab means with different superscript across column (within individual feed quality traits, but different nutrient gradient) differ significantly at $P = 0.05$; *K* potassium; S is for sulphur, *B* boron, *Zn* zinc, *CP* crude protein, *NDF* neutral detergent fibre, *ADF* acid detergent fibre, *ADL* acid detergent lignin, *IVODM* in vitro organic matter digestibility, *ME* metabolisable energy, *SN* sample number, Cereals residues include stalks and stubble (stems), leaves, and seed pods and does not include process residues; *NV* no value

3.2 Effects of extractable soil nutrient gradient on feed quality traits of cereals crop residues

To portray how feed quality of cereals CR is affected by the gradients of less often applied extractable soil nutrients (S, Zn, P, K and B), an example is provided by results shown in Table 4. Under low and medium levels of extractable S, the observed feed quality traits of cereals showed significant differences. When compared with low level of S, NDF, ADF, ADL showed a significant decline under medium level of S ($P = 0.01$), and contrastingly, the values of ME and IVODM improved significantly ($P = 0.01$). Despite observed increase, value for CP in medium S level was not significantly higher than in low level extractable S. Similarly, NDF, ADF and ADL values at high extractable Zn level was significantly lower than at the low and medium levels. High level of extractable Zn tended to improve the CP values. Also, high level of extractable *P* showed significantly lower values for NDF and ADF and higher value for ME and IVODM over the low *P* level.

Medium level extractable K showed a significantly higher value for CP. Values for NDF and ADF were significantly higher under high level than in the low and medium levels of extractable K. The high level of extractable K reduced IVODM significantly than in low and medium levels. Extractable B concentration tended to show similar trend as shown by K, but the CP value showed a declining trend under medium level of extractable B (Table 4).

3.3 Effects of balanced nutrient inputs on crop residues' feed quality and productivity

To understand whether the grain targeted nutrient inputs significantly affect CR feed quality traits, the results in Table 5 compare ME, IVODM and CP values under control and balanced nutrient treatments. Within the crop group, there were no significant differences between control and treatment for mean ME (MJ kg^{-1}), IVODM and CP (g kg^{-1}) in spite of an increase in CP by 3, 5 and 6 % for cereals, oil crops and pulses, respectively (Table 5).

Drastic changes were observed for digestible dry matter (DDM, kg m^{-2}) and ME productivity (ME MJ m^{-2}). Within the crop group, both ME and DDM showed significantly higher values for treatment (at $P = 0.05$) than the control. There was variation between crop group in terms of value gain on both ME and DDM productivity. Cereals and pulses residues showed the highest increase of 33 % over the control, followed by oil crops (22 %). Similar trends, but with higher magnitude of variation, were observed for digestible dry matter productivity (Table 5).

3.4 Effects of balanced nutrient inputs on gross potential benefits from milk production

Table 6 compares the effects of balanced nutrient inputs on gross potential farm financial return from milk. In all studied farming systems, the gross potential return from milk under treatment exceeded the control (Table 6). In the best case, the treatment was by about 40 % higher than the control as estimated for the millet-based oil crop production system. In the worst case, 22 % improvement on the potential gross financial return was estimated for maize-based sorghum production system (Table 6).

There was no apparent difference in the efficiency of utilization of ME between the treatment and the control. Only sorghum-based pulses had about 3 % improvement on Kl. This means that the differences in gross potential benefits, overwhelmingly, came from improved dry matter and associated ME productivity.

Table 5 Effects of balanced nutrient inputs (treatment) on in vitro organic matter digestibility (IVODM), metabolisable energy (ME) and crude protein (CP) of crop residues in semiarid region Karnataka, India

Crop groups	Group	SN	Mean value of feed quality traits				
			ME (MJ kg^{-1})	IVODM (%-DM)	ME (MJ m^{-2})	DDM (kg m^{-2})	CP (%-DM)
Cereals residues	Control	175	7.62 ± 0.50[a]	53.52 ± 2.86[a]	3.25 ± 1.62[a]	12.50 ± 5.84[a]	7.37 ± 1.49[a]
	Treatment	175	7.64 ± 0.53[a]	53.39 ± 3.04[a]	4.31 ± 1.84[b]	16.72 ± 6.67[b]	7.63 ± 1.49[a]
Oil crops residues	Control	132	7.75 ± 0.81[a]	56.59 ± 4.39[a]	1.44 ± 0.45[a]	6.47 ± 1.96[a]	15.20 ± 3.97[a]
	Treatment	132	7.78 ± 0.76[a]	56.66 ± 3.82[a]	1.76 ± 0.60[b]	7.83 ± 2.46[b]	15.98 ± 4.21[a]
Pulses residues	Control	112	7.64 ± 0.40[a]	53.37 ± 2.39[a]	2.10 ± 1.63[a]	8.14 ± 6.40[a]	8.62 ± 4.73[a]
	Treatment	112	7.73 ± 0.41[a]	53.71 ± 2.36[a]	2.77 ± 2.26[b]	10.78 ± 8.84[b]	9.11 ± 5.04[a]

ab means with different superscript across columns indicates the treatment and control within a crop group differ significantly at $P < 0.05$. Residues include stalks and stubble (stems), leaves, and seed pods and does not include process residues; *SN* sample number

Table 6 Effects of balanced nutrient input on efficiency of crop residues ME utilization, productivity and farm financial return per unit area in semiarid region Karnataka, India

Experiment group	Farming systems	Parameters to estimate the productivity and efficiency of utilization of ME							
		ME (MJ kg^{-1} of dry matter)	kl	Evl	ME (kg^{-1} of milk)	Dry matter ME (ha^{-1} year^{-1})	Potential milk yield (L ha^{-1} year^{-1})	Milk price (US\$ L^{-1} of milk)	Gross benefit (US\$ ha^{-1} year^{-1})
Control	Sorghum-based pulses	7.58	0.56	3.18	5.64	16,765	2,970	0.44	1,320
	Pulses-based oil crops	7.59	0.56	3.06	5.43	36,628	6,751	0.44	3,001
	Maize-based sorghum	7.37	0.56	3.18	5.68	48,205	8,479	0.44	3,769
	Millet-based oil crops	7.85	0.57	2.96	5.20	16,437	3,161	0.44	1,405
Treatment	Sorghum-based pulses	7.73	0.58	3.18	5.62	22,042	3,925	0.44	1,744
	Pulses-based oil crops	7.57	0.56	3.06	5.43	48,335	8,903	0.44	3,957
	Maize-based sorghum	7.32	0.56	3.18	5.69	59,142	10,386	0.44	4,616
	Millet-based oil crops	7.87	0.57	2.96	5.20	23,061	4,438	0.44	1,972

ME metabolisable energy, *Kl* the efficiency of utilization of ME for milk, *EV1* energy value of milk

4 Discussion and conclusions

4.1 The cost of soil nutrient depletion, in the mixed crop–livestock farming system, is beyond reducing grain yield

The soil test results revealed widespread deficiencies of OC, S, P, Zn and B. K was the only nutrient with occasional distribution of low level of availability across the observed fields. These trends in the present study are in agreement with those reported by Rajashekhara Rao et al. (2010), who studied nutrient management for the rainfed maize farming system in the semiarid region of Karnataka. The general trend in soil nutrient exhaustion can partly be accounted for by continuous cultivation, grain and residues outputs. For example, per cropping season 34 kg N and 5 kg P ha^{-1} (by cereals in residues) on average was removed by the production system, and there is a large variability among crops. If the above-stated depletion is added to the loss by soil erosion (e.g. Priess et al. 2005), the magnitude of nutrient depletion can be even higher. One of the major concerns in this regard is not only the inadequate mineral nutrient inputs by smallholder farmers, but also the slim opportunity to recycle these nutrients through livestock manure, mainly because of strong competition with the rural household energy supply and high labour requirement to transport and spread manure on farm plots.

What is appealing here is the fact that the implication of such persistent nutrient deficiencies was, most often, perceived from their impacts on reduced grain production (e.g. Rego et al. 2007; Rajashekhara Rao et al. 2010). The results of this study clearly demonstrated that the outcome of soil nutrient depletion, in a mixed crop–livestock faming system, is far beyond reducing grain production. It affects livestock feed quality and thus is strongly associated with the demand for resources (land and water Haileslassie et al. 2011a; Blümmel et al. 2009a, b). Such soil–crop–livestock continuum is seldom explored and rarely used to encourage smallholder farmers to improve soil nutrient management. So this knowledge can certainly build on the existing understanding of the need and benefits of balanced nutrient management in crop–livestock system.

4.2 Implications of the relationships of extractable soil nutrients with feed quality traits

One of the apparent observations from the present study is the inverse associations of the rarely replenished soil nutrients such as S, Zn, and P with the CR feed quality traits (NDF, ADF and ADL) for cereals and oil crops. Commonly, NDF, ADF and ADL are known as anti-feed quality factors and their relationships with feed ME and IVODM are inverse (e.g. Singh and Shukla 2010).

How S reduces NDF, ADF and ADL in CR of cereal crops and increases IVODM and ME is rarely reported under smallholders' management. Study by Mathew et al. (1994) on the effects of S fertilization of Bermuda grass and its effects on digestion of N, S and fibre by non-lactating cows illustrated an improvement in IVODM when S was added. In another study by Ahmad et al. (1995) on the effects of S fertilization on chemical composition, ensiling characteristics and utilization by lambs of sorghum silage demonstrated that S fertilization increased S, N, K and manganese (Mn) concentrations. Such synergetic interactions can influence the ash and crude protein content of a feed, as demonstrated by our results, and thus impacts positively the feed quality. Similarly, Rees and Minson (1978) also reported that S fertilization increased digestibility of Pangola grass. Whether the nitrogen fixation by pulses and oil crops shifted the N: S ratio (Jemal et al. 2010) and thus affected the positive contribution of S to feed quality traits of pulses and oil crops, as observed in cereals, is a point for further investigation. Probably aggregation at the crop level also hides information on how individual crops behave under different levels of S. For example, unlike for all pulses (Table 3), the relationship of S with feed quality traits in chickpea was remarkable, positive and significant relationship with CP, and inverse and significant relation with ADF and ADL. For oil crops, the trend is similar both at the crop level or crop group level. Unlike in the case of S, the relationships of Zn with NDF, ADF and ADL were less consistent. The inverse and statistically significant correlations among Zn and NDF, ADF and ADL in cereals could be explained by the role of Zn in protein synthesis (Cakmak et al. 1989), while the positive and insignificant association in pulses and oils is not clear.

The relation of boron with NDF, ADF and ADL for cereal and oil crop group was significant and positive. This implies a negative impact on feed quality traits such as ME and IVODM, but care is needed in interpreting such relation as extractable B concentration under cereals and oil crop varies only from low to medium (Table 3), and thus, it is hardly possible to see the impact of increasing B concentration. To understand more on such relationships, we selected chickpea a pulse crop which has all the three levels of B and a different picture emerged: boron showed a significant and inverse relationship with NDF, ADF and ADL and positive and significant relation with CP (Zehirov and Georgiev 2005). Similar trends were observed for soybean (oil crop). From a study on the influence of B on forage quality of pasture legume, Schmidt et al. (2000) also reported that B application improved IVODM.

Soil K also showed clear relation with feed quality traits under examination. At crop group level, the relationships of NDF, ADF and ADL with extractable K were positive and significant. Contrastingly, an inverse relation was observed with CP contents for pulses and cereals. Usually, the relationship between CP and fibres is negative, and thus, the effects of K were in two ways: it reduced CP and increased fibre. From the study on the effects of P and K on growth, yield and fodder quality of forage sorghum cultivars, Pholsen and Suksri (2007) reported that the effects of different level of K reduced CP, though not significantly, but stimulated the production of fibre. Perhaps related issue is that K is known for improving plant resistant to insect attack through development of thick cell wall (e.g. Brady and Weil 2002). Because of the fact that >90 % of observed fields had medium and high levels of extractable K, crops probably had luxurious consumption of this nutrient, which might have led to positive influence on fibre production (Brady and Weil 2002).

In conclusion, the observed correlations among soil nutrient status and feed quality traits are encouraging to improve CR feed quality through improved soil fertility management. For some of the nutrients, insignificant differences of feed quality traits across extractable soil nutrient gradients suggest the need to understand the lowest concentration of individual nutrients that stimulate the relationships and also upper cut-off points beyond which the extractable nutrient level has no positive influence on feed quality. Observed variation within and between crop groups and crops illustrates the sensitivity of different crops to different nutrients and their concentration. Therefore, fertilizer recommendation has to put both soil and crop type and the use of CR into perspectives. Literature review suggests varietal level differences and variation in responses to similar level of soil nutrient, which is usually accounted for by variation in the proportions of plant morphological fractions (leaves and stems), rather than differences in cell wall composition per se (e.g. Reed et al. 1988). Future research must look at how the different morphological features under different extractable soil nutrient level and how this relationship affects CR feed quality traits in various farming systems.

4.3 Improved fertilizer input on crop land reduces livestock feed quality and quantity gaps

Results given in Table 5 compare the effects of improved fertilizer inputs on feed ME, DDM and CP. There were no statistically significant differences between the treatment and control for feed quality traits (ME, IVODM and CP) for crop groups. But all the parameters showed higher values for treatment compared to the control. Important observations were the significant effects of balanced fertilizer input on feed quality of soybean: the treatment has significantly increased IVOMD and ME values. Similarly, millet residues showed a significant reduction in ADL and ADF in the treatment. Here, it is important to understand as to why the bulk of the crops did not show a significant change in feed quality traits as a result of the balanced nutrient management treatment. Although further investigation involving grain nutrient concentration is important, probably such a general trend can be also ascribed to the dilution effects on nutrients that are associated with CR feed quality traits (e.g. Jarrell and Beverly 1981).

What is equally important for smallholder farmers, in the view of widespread over-stocking in the study farming system (Table 1), is ME productivity (ME ha^{-1}) and the efficiency of utilization of ME by ruminant [e.g. for milk (Table 6)]. In this regard for crop group, major increase in ME ha^{-1} was recorded (Table 6) for cereals (33 %), while the least productivity gain was for oil crops (22 %). The fact that farmers are producing range of crops (Table 6); and varieties, crop group level improvement in ME productivity might not be explanatory and thus farming system level observation is important. At farming system scale, the ME productivity gain was highest for millet-based oil crops (40 %), followed by pulses-based oil crops farming systems (32 %).

The simplest measure of change in feed quality is to estimate the volume of potential milk produced per MJ of ME. This is an estimate of the efficiency at which energy consumed (input) appears as milk production (output). From the four studied farming systems, only sorghum-based pulses showed improvement in CR feed ME efficiency (Table 6). The gain in gross potential financial benefits from milk was more remarkable when the benefits from improved ME productivity and feed ME efficiency were aggregated (Table 6).

4.4 Implications for future development and policy making

From this study, it is apparent that balanced nutrient inputs reduced the feed quality and quantity gaps. This knowledge can build on the currently perceived need and benefits of balanced nutrient replenishment in crop–livestock system and therefore helps to convince policy makers and farmers. The study also illustrated that the magnitude of the effect of balanced nutrient input on feed quality and quantity is dependent on farming systems (crop type, crop combination, livestock herd structure etc.…). Future development efforts must include not only fertilizer inputs, but also optimum mix of system's components.

It needs also to emphasize that the estimated potential benefits can be realized only if the animal genetic base is not a limiting factor. Policy incentive for improved livestock management must be in place. In general, improvement in livelihoods of farmers and enhancing sustainable ecosystem management in the mixed crop–livestock farming system are not feed quality improvement per se. It needs integrated approaches that involve, for example, optimum resources (e.g.CR) allocation for different uses, improved livestock breed, better management of herd structure, animal health, etc.

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