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Review

Livestock water productivity: feed resourcing, feeding and coupled feed-water resource data bases

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Abstract. While water requirement for livestock is widely perceived as daily drinking water consumption, ~100 times more water is required for daily feed production than for drinking water. Increasing livestock water productivity can be achieved through increasing the water-use efficiency (WUE) of feed production and utilisation. The current paper briefly reviews water requirements for meat and milk production and the extent of, and reason for, variations therein. Life-cycle analysis (LCA) can reveal these variations in WUE but LCA are not tools that can be employed routinely in designing and implementing water-use-efficient feed resourcing and feeding strategies. This can be achieved by (1) choosing agricultural by-products and crop residues where water applications are partitioned over several products for example grain and straw (or food and fodder) contrary to planted forage production where water and land have to be exclusively allocated to fodder production, (2) select and breed WUE crops and forages and exploit cultivar variations, (3) increase crop productivity by closing yield gaps; and (4) increase per animal productivity to reduce the proportion of feed (and therefore water) allocated for maintenance requirement rather than productive purposes. Feed-mediated WUE of dairy buffalo production on almost completely (94%) by-product-based feeding systems could be reduced from 2350 to 548 L of water per kg of milk by the combined effect of increasing basal ration quality in a total mixed ration, which resulted in increased milk yield of ~30%, and by increasing crop productivity from 1 t (actual crop yield) to 3 t (potential crop yield). Exemplary, multi-dimensional sorghum improvement using staygreen quantitative trait loci (QTL) introgression for concomitant improvement of WUE of grain and stover production and stover fodder quality showed opportunities for further linked improvement in WUE of crop and livestock production. Metabolisable energy (ME) yield under water stress conditions measured in lysimeters, (which measure crop water transpired) ranged QTL dependent from 16.47 to 23.93 MJ ME per m^3 H_2O. This can be extrapolated to 8.23–11.97 MJ ME per m^3 H_2O evapotranspired under field conditions. To mainstream improvement in WUE of feed resourcing and feeding, the paper suggests the combination of feed resource databases with crop–soil–meteorological data to calculate how much water is required to produce the feed at the available smallest spatial scale of crop–soil–meteorological data available. A framework is presented of how such a tool can be constructed from secondary datasets on land use, cropping patterns and spatially explicit crop–soil–meteorological datasets.

Additional keywords: agricultural by-products, environmental sustainability, resource-use efficiencies.

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Introduction

Agriculture is the largest consumer of water, accounting for 72% of total water use (Steinfeld *et al*. 2006). As demand for industry, municipal and other water uses increase, less water will be available for agriculture and food production, despite increasing food demand, specifically for animal-sourced food (Delgado *et al*. 1999). Production of food needs to be increased and the water-use efficiencies (WUE) of food production need to be improved, and scope for this exists (Comprehensive Assessment of Water Management in Agriculture 2007). Water requirements for food production can vary widely; for example, for plant-sourced food from 0.5 m^3/kg potato to 3 m^3/kg rice and for animal-sourced food from 3.5 m^3/kg in broiler production to 100 m^3/kg in beef production, with directly plant-sourced food such as grains and vegetables usually produced in more water-use-efficient ways (Pimentel *et al.*

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1997). High water requirements are intuitively often connected with very intensive systems, but extensive systems are generally less effective relative to the amount of agricultural output from water input (Zwart and Bastiaanssen 2004). Singh *et al*. (2004) drew attention to the sometimes surprisingly high water needs for extensive dairy production in India, calculating that in the state of Gujarat, the heartland of the 'white revolution' (widespread increase in milk production), an average of 3.4 m^3 of water is required for the production of 1 kg of milk. The global average is 0.9 m^3 and the authors traced high water needs to feed resourcing and production, concluding that on average 10 000 L of water was required to produce the daily feed for one single dairy animal. Conventionally, the relationship between livestock and water is associated with drinking water requirements and the fact that much more water is required for evapotranspiration in feed production still escapes the awareness of many livestock nutritionists. They rarely include water requirement assessments in feed resourcing and ration design.

Blümmel *et al*. (2009) revisited the data of Singh *et al*. (2004) and calculated that the amount (kg) of planted forage in the ration was positively correlated (P = 0.014) with the amount of water required for the production of 1 kg of milk, explaining 66% of the variation in this relationship. A model combining the amount of concentrate fed in a multiple regression with the amount of planted fodder fed explained 82% of the variation in water needs per unit of milk (L H_2O/L of milk = –191 + 265 × planted fodder – 433 × concentrate). In planted forage production all water used has to be exclusively allocated to this specific feed resource, in contrast in agro-industrial by-products such as bran and oil cakes and crop residues such as straw, stover and haulms water is partitioned across primary and secondary products. At comparable livestock productivity levels, by-product-based feeding systems are inherently more WUE than feeding systems based on planted forages or primary crop products. The present paper investigates several approaches to improve the WUE of livestock production. This can be achieved by (1) choosing agricultural by-products and crop residues and combining them in livestock nutritionally well balanced rations, (2) selecting and breeding WUE crops and exploit cultivar variations, (3) increasing crop productivity by closing yield gaps, and (4) increasing per animal productivity to reduce the proportion of feed (and therefore water) allocated for maintenance rather than productive purposes.

By-product-based feeding systems: reinforcing effects of intensification of livestock and crop production on increasing livestock water productivity

Selection of superior basal diet components and targeted supplementation

Key by-product feed resources are agro-industrial by-products and crop residues with the latter being of particular importance in developing and emerging countries where they commonly account as the single most important fodder resource (Blümmel *et al.* 2012). Worldwide total crop residue production is estimated at 3.8 billion metric tonnes, with cereals contributing 74%, sugar crops 10%, legumes 8%, tubers 5% and oil crops 3% (Lal 2005). Crop residues are generally considered to be of low nutritive quality, but this statement implicitly relates to cereal residues, since leguminous residues can have excellent fodder quality (Prasad *et al.* 2010). The widespread availability of crop residues and the extent of their use as livestock fodder mark them as a strategic feed resource of the highest order. Furthermore, it is important to realise that crop residues are among the few feed resources that do not need a specific allocation of water (and land for that matter), because the crops are grown largely, though not exclusively, for the production of the primary products of grains and pods. However, in this context it is interesting to note that the monetary value of crop residue relative to grain is getting narrower and in sorghum stover and grain in India have now reached approximately parity (Sharma *et al.* 2010).

Until recently crop residue fodder traits were largely ignored in crop improvement, although farmers and fodder traders were well aware of differences in the fodder quality of crop residues even within the same species (Kelley *et al.* 1996). Blümmel and Parthasarathy Rao (2006) surveyed major sorghum stover traders supplying urban and peri-urban dairy producers around Hyderabad in rain-fed India from 2004 to 2005 and observed that a difference of 5% points in *in vitro* digestibility (47% vs 52%) between the poorest- and highest-quality sorghum stover was associated with a price premium of more than 25%. In collaboration with the commercial feed processor Miracle Feed and Fodder Pvt (Shah 2007), which marketed a total mixed ration (TMR) feed block consisting of 94% of crop residues and agro-industrial by-products (see also Table 1), experimental feed blocks were produced using the poorer- (47% digestibility) and higher-quality

Table 1. Ingredients of a total mixed ration (TMR) feed block and crude protein (CP) and metabolisable energy (ME) of TMR based on two different sorghum stover and voluntary feed intake (VFI) and milk potential of dairy buffalo fed the two TMR

Ingredient	%	TMR composition and response of dairy buffalo		
Sorghum stover	50		TMR stover 47%	TMR stover 52%
Bran/husk/hulls	18	CP (%)	17.1	17.2
Oilcake	18	ME (MJ/kg)	7.37	8.46
Molasses	8	VFI (kg/day)	18.0	19.7
Grain	4	VFI (g/kg liveweight)	33	36
Minerals, vitamin, urea	2	Milk potential (kg/day)	9.9	15.5

(52% digestibility) sorghum stover and tested with a commercial dairy buffalo producer (Anandan *et al.* 2010).

Several important conclusions can be drawn from this work. Very importantly, an intuitively small difference in basal ration digestibility (here sorghum stover) of 5% points can result in an increase in milk yield of more than 5 kg per animal per day by the accumulative effects of higher ration metabolisable energy (ME) and higher intake (Table 1). Second, an almost completely by-product-based ration can support milk yields of close to 16 kg of milk, which is about thrice the Indian average (Blümmel *et al.* 2013*a*). These are respectable levels of livestock performance and these data were obtained with dairy buffalo, which have very high milk fat contents (~7% in the cited work) and extrapolation of these data to dairy cattle suggests a potential daily milk yield of up to 20 kg on almost completely by-product-based rations.

The findings presented in Table 1 also have implications for livestock water productivity. Using average Indian crop yields, harvest indices and conversion factors for primary product to by-product such as oilcakes, bran and molasses, total water requirements to produce one TMR feed block of 15 kg was estimated at 19.39 m^3 (Table 2). Daily milk yields of 15.5 and 9.9 kg will then require 25.47 and 23.27 m^3 of total H_2O and 1643 and 2350 L of H_2O per kg of milk, respectively. Considering the substantially different WUE per unit milk produced, attributing the same water requirement (19.39 m^3) to both TMR feed blocks is not convincing. In other words, feed-related WUE expressed on biomass and/or dry matter (DM) yield, contain limited information. Actual milk yields (or general animal performance) will not be known when designing rations and planning new feeding regimes but animal nutritionists will use ME and protein values and intake predictions to calculate prospective and targeted animal performances. WUE for feed production can then be expressed relative to ME and in the case discussed here 153 and 175 L of H_2O are required to produce 1 MJ ME in TMR feed blocks with higher and poorer quality sorghum stover, respectively.

Expressing water requirement relative to ME content/yield (and/or protein content for that matter in high protein feedstuffs) seems a good choice avoiding the shortfalls of computing mere biomass yield per unit water input while still offering the possibility of estimating financial water use efficiencies from the calculation of prospective and targeted animal performance and its financial value (see also below).

Table 2. Water requirements for total mixed ration (TMR) ingredients and for TMR feed block

n/a, not applicable; n/c, not calculated

Ingredient	%	kg of ingredient per m^3 of H_2O	m^3 of H_2O per 15 kg TMR
Sorghum stover	50	0.70	10.71
Bran/husks/hulls	18	0.67	4.03
Oilcakes	18	0.52	1.404
Molasses	8	5.2	1.56
Grains	4	2.8	1.68
Minerals, vitamins, urea	2	n/c	n/c
Total	100	n/a	19.39

This difference in WUE relative to ME (153 vs 175 L of H_2O) is smaller than the WUE expressed relative to milk produced (1643 vs 2350 L of H_2O) because the water to feed ME relationship does not capture the intensification effects of higher feed quality that translates also into higher feed intake and a shift in feed utilisation from maintenance to production (Blümmel *et al.* 2013*a*). In case of the milk productivity and water requirement data reported in Tables 1 and 2, at 10 kg of milk per day about 50% of the water would need to be allocated for feed maintenance requirement, decreasing to less than 30% at 15 kg per day. In contrast, at 3 kg of milk daily more than 70% of the water is used for feed maintenance requirements (calculated from Blümmel *et al.* 2013*a*). It is therefore important to realise that intensification of crop production would contribute immensely to livestock water productivity. For example water requirements used in Table 2 were based on actual (low) average crop yields in small farmers' fields in India. The yield gaps under those conditions are estimated at ~1 : 3, in other words adoption of rather simple management options such as timely planting and weeding, and fertiliser application, could triple crop yields. This would reduce water requirements for the above described TMR to ~6.46 m^3 per block and water requirement per kg of milk to between 548 and 783 L. To conclude, concomitant intensification of crop and livestock production will have hugely beneficial effects on livestock water productivity measured as agricultural and livestock output per unit water. These relationships need to be compared and aligned with an economic assessment looking at $US/$m^3$ H_2O input and output. It also important to note that livestock outputs entail less tangible and quantifiable products such as draught power, manure and a range of social services, which will need to be included into truly comprehensive livestock water productivity analysis (Peden *et al.* 2007; Descheemaeker *et al.* 2010; Haileslassie *et al.* 2011).

In East Africa, Descheemaeker *et al.* (2011) and Gebreselassie *et al.* (2009) reported livestock water productivity values ranging between US$0.01 and US$0.4 m^{-3} H_2O. The least efficient value was calculated for a local low-productive animal while the higher value was for both improved genetics (cross-bred) and feed. When converted into financial water productivity, the results reported in Table 2 translate into US$0.28 and US$0.41 m^{-3} H_2O for TMR 47% and 52%, respectively. In other words, in production- and market-oriented systems in East Africa (cross-bred animals) and India (dairy buffalos) livestock water productivity when expressed as US$ return per water input broadly showed similar ranges.

Improving fodder value and WUE of basal diets concomitantly by multi-dimensional crop improvement

The findings presented and discussed in Tables 1 and 2 demonstrate that apparently small differences in fodder quality of basal rations (here sorghum stover) can have a significant impact on livestock production and livestock water productivity. The magnitude of difference i.e. ~5% points in digestibility and more was found in straw, stover and haulms of a range of cereal and leguminous crops (Sharma *et al.* 2010; Blümmel *et al.* 2012, 2013*b*). These differences can be exploited by simply phenotyping for crop residue fodder quality during multi-dimensional crop improvement (Sharma *et al.* 2010; Blümmel *et al.* 2012, 2013*b*). These phenotypings essentially detected cultivar-dependent variations in crop residue fodder quality traits, which were largely unintended and which came about by chance. However, crop residue fodder traits can also be actively improved by targeted genetic enhancement, using conventional (Bidinger *et al.* 2010; Ertiro *et al.* 2013; Zaidi *et al.* 2013) and molecular breeding approaches (Nepolean *et al.* 2006; Vinayan *et al.* 2013; ACIAR 2014). In light of the following discussions about feed resource databases below, it is important to point out that these multi-dimensional crop improvement collaborations have strong environmental components. New dual/multi-purpose cultivars are tested across widely different regions and seasons (Blümmel *et al.* 2010; Ravi *et al.* 2013) and management conditions (Bidinger and Blümmel 2007; Blümmel *et al.* 2007), providing potentially very targeted input variables into such feed resource databases as exemplified in Tables 3 and 4 below.

Above-mentioned multi-dimensional crop improvement efforts focussed mainly on increasing grain and pod yield and crop residue yield and fodder quality. As argued by Vadez *et al.* (2011*a*), additional traits can be targeted, for example WUE. These authors introgressed 31 sorghum lines with different staygreen quantitative trait loci (QTL) (Vadez *et al.* 2011*b*; ACIAR 2014) and suggested that staygreen introgression may concomitantly improve WUE and stover fodder quality. Blümmel and colleagues (ACIAR 2014) investigated the same sorghum lines for a range of fodder quality traits and the relationships between stover ME content and stover WUE are presented in Fig. 1*a*, *b*.

Table 3. Summary of feed supply and demand in India, drawn from information published by NIANP (2003)

	Feed resource (10^6 t)	Feed resource (%)
Greens		
From forest area	89.37	4.5
From fallow lands	23.21	1.2
From permanent pastures and grazing areas	28.70	1.4
From cultivable waste lands and miscellaneous tree crops	17.51	0.9
From planted fodder crops	303.26	15.1
		23.0
Crop residues		
Coarse	154.83	27.8
Fine straw	194.11	34.8
Leguminous straw	44.44	8.0
		70.6
Concentrates		
Oil cakes	15.76	2.8
Brans	13.29	2.1
Grains for feeding livestock	5.74	1.0
Chunnis (leguminous husks, hulls etc)	0.53	0.1
		6.3
Feed/nutrient requirements versus *feed availability*		
	Deficit (%)	
DM	6.0	
Digestible crude protein	61.0	
Total digestible nutrients	50.0	

Generally, differences in WUE were more expressed under water-stressed than under well watered conditions. This was because the physiological traits underlying the QTL had mostly an effect under water-limited conditions. Among the three highest WUE, that is kilogram of stover produced per m^3 H_2O, stover ME per kg stover varied dependent on sorghum line by ~1 MJ (Fig 1*a*, *b*), which is of a similar order to the ME difference observed in the two TMR feed blocks described and tested in Table 1. In addition, WUE in sorghum stover in Fig. 1*a*, *b* can be several-fold higher than that of stover used for the TMR WUE calculations (0.70 kg/m^3 H_2O). It should be noted here that the calculations of WUE from Figs 1 and 2 are coming from lysimetric assessment of WUE, where most of the component of soil evaporation is prevented by covering the soil surface with a plastic sheet and plastic beads (Vadez *et al.* 2011*a*, 2011*b*). Therefore, WUE was calculated and presented on the basis of crop water transpiration and not on the basis of crop evapotranspiration. If we consider the evapotranspiration of the crop to have been about twice that of the crop transpiration, the WUE data of Fig. 1*a*, *b* should be divided by a factor of two to be comparable to field estimates of crop WUE. When the sorghum lines were grouped for staygreen QTL they were introgressed with, under well watered conditions WUE for whole-plant production (i.e. grain and stover) ranged from 3.76 to 4.76 kg/m^3 H_2O, for stover production from 2.52 to 2.80 kg/m^3 H_2O, with stover ME production ranging from 18.37 to 21.49 76 MJ ME/m^3 H_2O (see Fig. 2).

Under water-stressed conditions, WUE for whole-plant production ranged from 3.82 to 4.54 kg/m^3 H_2O, for stover production from 2.3 to 3.43 kg/m^3 H_2O, with stover ME production ranging from 16.47 to 23.93 MJ ME/m^3 H_2O (see Fig. 3).

In crop physiology, the definition of WUE is in fact inverse to the evaporative demand (Bierhuizen and Slatyer 1965), such that transpiration efficiency, which is higher for C_4 than for C_3 crops. Therefore, as a first cut, the water productivity of residues from C_3 crops such as wheat or rice would be lower than the water productivity of crops such as sorghum or maize. As another criterion to differentiate scenarios, the water productivity of residue would be higher if crops are grown under conditions of low evaporative demand. Beyond these cardinal crop and growth condition factors affecting the water productivity of feed resources, there exists a lot of genetic variability for water productivity within these cardinal factors (see a recent review by Vadez *et al.* 2014). Another important factor driving the water productivity of crop is the evaporative demand prevailing at the location and timing of production. Therefore, taken together, there is room to synergistically enhance water productivity of feed, playing on crops, growth conditions, and cultivars.

Approaches for complementing feed resource databases by water requirements

Feed database requirements and possible structures

Complementing feed resource databases by data about the amount of water required to produce them consists of two

Table 4. Subclasses of feed resources, their metabolisable energy content (ME, MJ/kg), assumption and spatial units
Feed subclasses and assumption were extracted from the NIANP 2003 database

	ME mean[A]	ME range[A]	Assumption	Spatial units
		Greens		
Cultivable wasteland	–	–	Total area, 1 t/ha	Village
Current fallows	–	–	Total area, 1 t/ha	↓
Forests	–	–	50% of area accessible, 3 t/ha	Taluk
Miscellaneous trees	–	–	Total area, 1 t/ha	↓
Other fallows	–	–	Total area, 1 t/ha	Mandal
Permanent pasture	7.54	6.64–8.39	Total area, 5 t/ha	↓
Cultivated forages crops:			4% of cropped area, 40 t/ha	District
Legumes	8.21	7.75–8.79	–	
Grass	7.71	6.84–8.91	–	
		Crop residues		
Coarse straw				
Sorghum (kharif season)	6.72	5.16–7.95	Harvest index 0.29	
Sorghum (Rabi season)	7.63	6.28–9.10	Harvest index 0.29	
Pearl millet	5.98	3.37–8.89	Harvest index 0.29	
Barley	6.63	6.37–6.76	Harvest index 0.44	
Maize	7.22	6.10–8.08	Harvest index 0.29	
Oats	7.85	7.00–8.65	Harvest index 0.33	
Smaller millet	7.39	7.07–7.99	Harvest index 0.29	Village
Other cereals	–	–	Harvest index 0.33	↓
Sugarcane tops	–	–	Harvest index 0.25	Taluk
				↓
Fine straw				Mandal
Rice	–	4.28–8.55	Harvest index 0.44	↓
Wheat	–	4.51–8.02	Harvest index 0.50	District
Finger millet	–	7.07–7.99	Harvest index 0.33	
Legume straw				
Groundnut	8.34	5.61–10.43	Harvest index 0.37	–
Chickpea	7.74	4.45–9.32	Harvest index 0.37	
Black lentil	8.32	7.40–9.25	Harvest index 0.37	
Mung bean	8.27	7.68–9.10	Harvest index 0.37	
Pigeon pea	7.73	7.22–8.48	Harvest index 0.37	
Soybean	8.32	7.40–9.25	–	
Cowpea	8.46	7.82–9.19	–	
Lablab	8.22	7.10–9.12	–	
		Concentrates		
Grains				
Pearl millet grain	10.98	10.39–1142	0.05 of total grain production	
Barley grain	–	–	0.10 of total grain production	
Maize grain	13.08	12.11–13.83	0.10 of total grain production	
Oat grain	–	–	0.10 of total grain production	
Other cereal grain	–	–	0.10 of total grain production	
Rice grain	–	–	0.02 of total grain production	
Wheat grain	–	–	0.02 of total grain production	
Sorghum grain	13.14	12.81–13.71	0.05 of total grain production	
Small millets (teff)	10.90	10.72–11.10	0.10 of total grain production	
Cakes				Village
Coconut cake	–	–	0.63 of nut yield	↓
Cotton cake	7.65	5.92–9.41	0.50 of seed yield	Taluk
Groundnut cake	8.32	7.67–8.98	0.70 of seed yield	↓
Linseed cake	–	–	0.70 of seed yield	Mandal
Niger cake	–	–	0.70 of seed yield	↓
Rape and mustard cake	10.67	10.49–10.86	0.70 of seed yield	District
Sunflower cake	–	–	0.70 of seed yield	
Safflower cake	–	–	0.70 of seed yield	
Sesame cake	10.53	10.33–10.72	0.70 of seed yield	

(*continued next page*)

Table 4. (*continued*)

	ME mean[A]	ME range[A]	Assumption	Spatial units
		Bran		
Maize bran	9.16	7.68–10.51	0.08 of grain yield	
Millet bran	8.94	7.63–9.89	0.08 of grain yield	
Rice bran	–	–	0.08 of grain yield	
Wheat bran	11.20	10.93–11.46	0.08 of grain yield	
		Pulse husk/pod		
Chickpea pods/husk	8.82	8.74–8.95	0.03 of grain	
Black lentil pods/husk	–	–	0.03 of grain	
Mung bean pods/husk	–	–	0.03 of grain	
Moth bean pods/husk	–	–	0.03 of grain	
Pigeon pea pods/husk	9.11	8.94–9.24	0.03 of grain	
Other pods/husks	–	–	0.03 of grain	

[A] ME values are from ILRI Patancheru database (http://ilrihyd.wikispaces.com, accessed 5 July 2014).

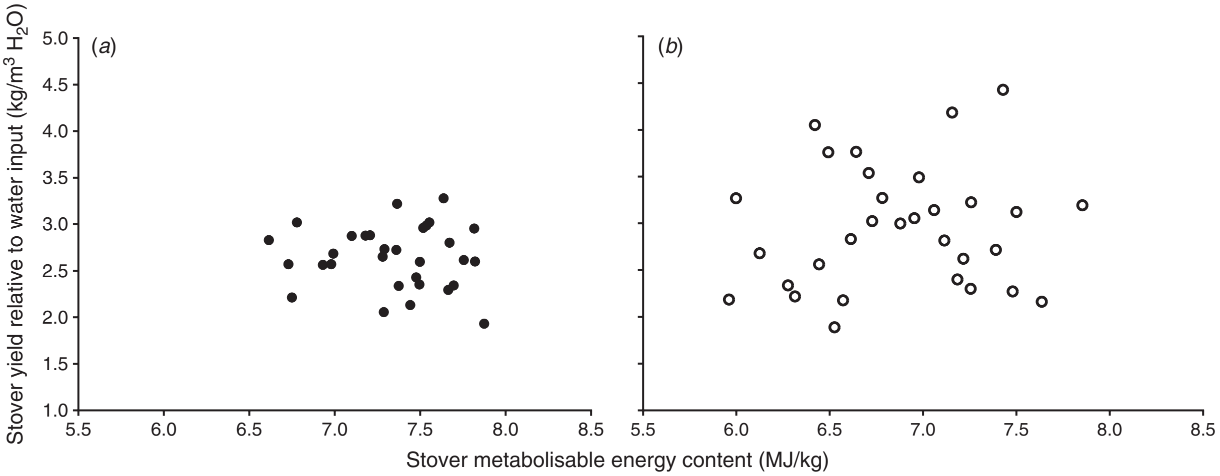

Fig. 1. (*a*) Stover metabolisable energy content and stover produced from 1 m^3 of water under well watered conditions in 31 sorghum lines introgressed with staygreen qualitative trait loci. (*b*) Stover metabolisable energy content and stover produced from 1 m^3 of water under water-stressed conditions in 31 sorghum lines introgressed with staygreen qualitative trait loci.

major steps: (1) constructing a feed database; and (2) propose causal relationships between feed production and water depletion and practical approaches on how to quantify the latter. The estimations of the quantity and quality of feed available and the generation of feed demand–supply scenarios can be tedious and complex, particularly when required baseline data are lacking. To be useful for decision making, they have to be down-scalable, or ideally, to be constructed for small administrative units. It has been suggested that the first steps in constructing a feed database depend mainly on availability of data sources (identification and description of land-use pattern at a sufficiently small scale or for disaggregated administrative units, such as village, district, state or region (NIANP 2003; Ramachandra *et al.* 2007; van Breugel *et al.* 2010). The challenge is that few comprehensive country-level datasets about feed supply and demand exist for developing and emerging countries.

As an exception, India has recently systematically quantified countrywide feed demand and supply by coordinated central government and state efforts (NIANP 2003). Major feed classes and their contributions are summarised in Table 3. This survey shows that, on a DM basis, crop residues were the single most important fodder resource, contributing ~71% to the overall feed resources. The area under planted forage contributed ~23% and was rather stagnant during the past two decades, increasing merely from 297 120 000 t in 1986 to 303 269 000 t in 2003. Fodder from common property resources, forests, pastures and fallow lands constituted less than 16% of the available fodder. Also, notable was that concentrates represented a very low proportion (<7%) of the available feed resources, and there was no indication of any rapid increase in their use (Table 3). The countrywide gap between feed demand and supply derived from the livestock census was minor for feed quantity (DM) but was large in regard to feed quality, since the estimated annual feed DM deficit was only 6%, while digestible crude protein and total nutrients were estimated to fall short by 61% and 50%, respectively (NIANP 2003).

The feed database as summarised in Table 3 would be unsuitable for complementation with water requirement estimates. However, the Indian NIANP database is built up

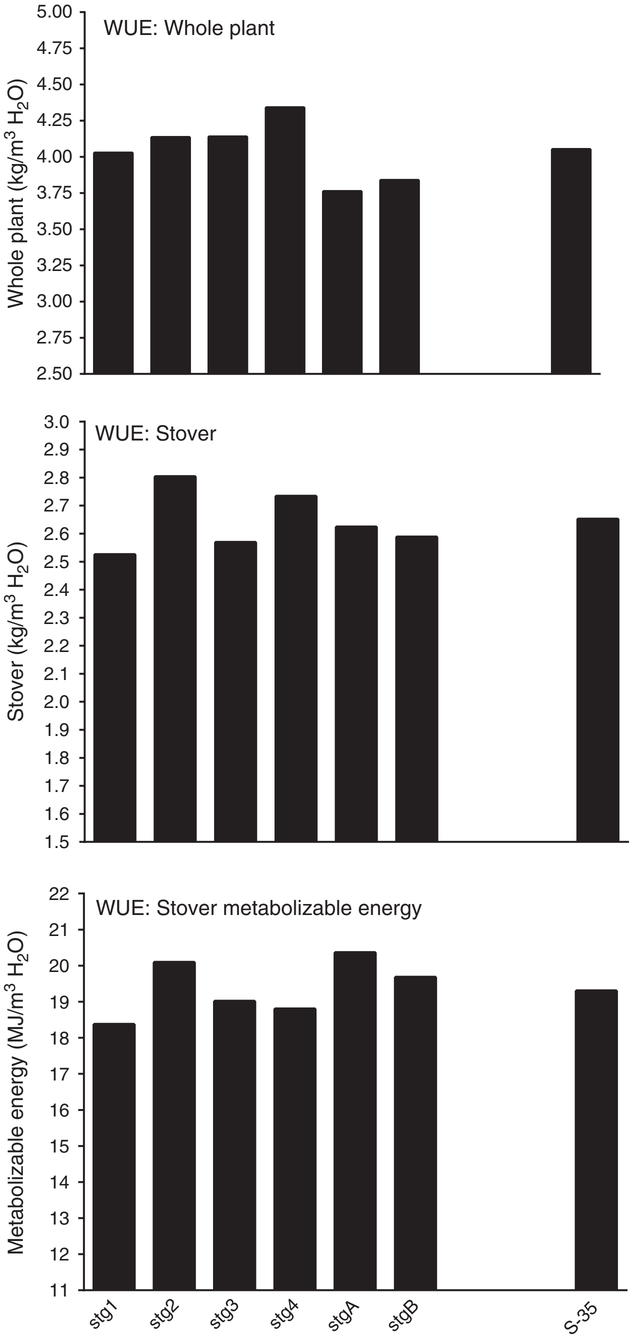

Fig. 2. Staygreen qualitative trait loci-associated water-use efficiencies (WUE) in sorghum background S-35 under well watered conditions.

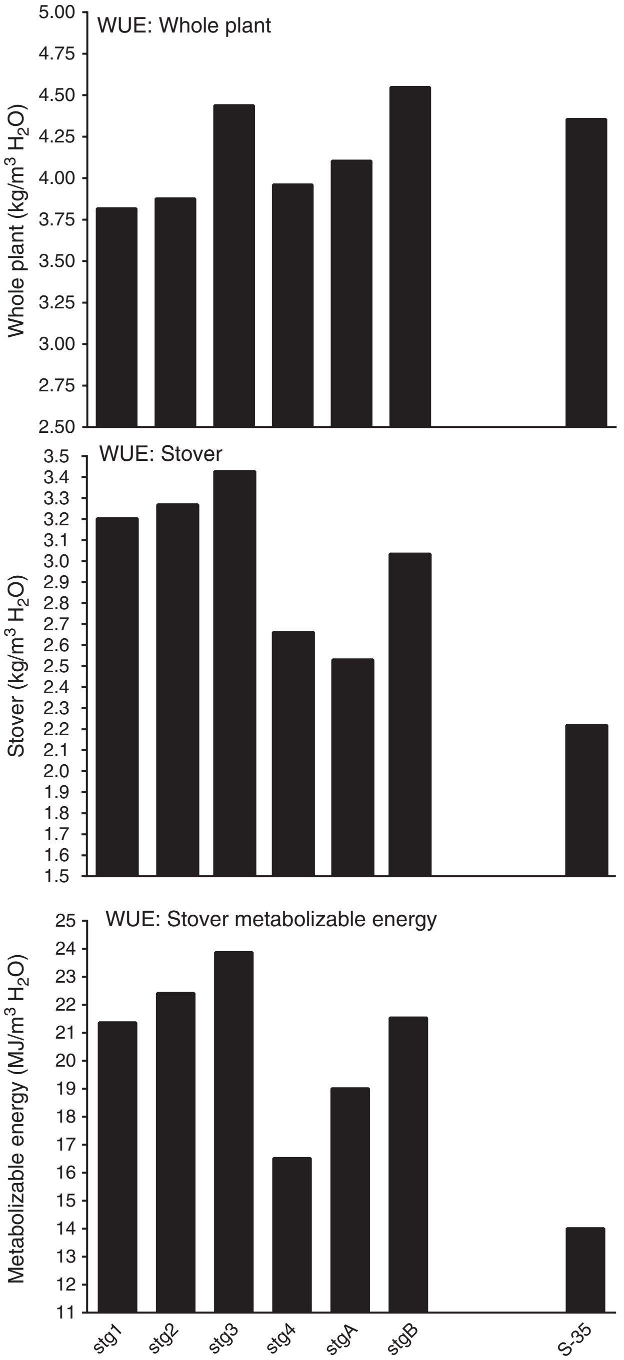

Fig. 3. Staygreen qualitative trait loci-associated water-use efficiencies (WUE) in sorghum background S-35 under water-stressed conditions.

from very detailed information about specific feed resources (Table 4), starting from village level, although generally presented as aggregations at district levels. If district-level data are considered to be too general, disaggregation is thus possible from District to Mandal to Taluk to Village level. The data are derived from data on land-use and copping pattern. Feed resource availability is then based on these, in combination with assumptions about, for example, yield, crop biomass partitioning into grain, straw, stover, haulms, bran and cake (Table 4). Assumptions about how much of the potential feed resources are actually available for feeding rather than used for competitive purposes such as paper industry and conservation agriculture, are applied. Approximate fodder-quality indices such as digestible crude protein and total digestible nutrients are included at different tiers of the feed database (NIANP 2003; Ramachandra *et al.* 2007).

The many assumptions and/or constants used are temporary compromises that can act as place holders for more targeted and more specific input variables. For example, as described above, much more specific data are generated from multi-dimensional crop improvement and are included in Table 4 as means and ranges in feed and fodder ME. This is in stark contrast to the assumed digestible protein and total digestible nitrogen values in the original NIANP 2003 database, which were almost identical across whole-feed subclasses (values not shown). Substituting feed and fodder trait mean values and constants by more feed source-, crop-, cultivar-, and location-specific values seems a challenge. However, there are related research and extension projects in India (Garg *et al.* 2013) and elsewhere (FAO 2012) that attempt to describe feed resources, and especially variations in fodder quality and even fodder prices, on scales small enough to provide IT supported farmer-specific ration-balancing programs on a village level. Combining efforts with such projects and global institutions as FAO and using the facilities of IT platforms will make generation of feed databases with more specific and detailed information feasible.

Framework to combine feed-resource databases and water-input requirement estimates

Estimation of water investment in livestock feed production is data intensive and complex (Peden *et al.* 2007; Descheemaeker *et al.* 2010; Haileslassie *et al.* 2011). Compounding factors include, for example, multiple use of agricultural water, limited knowledge of water productivity on natural pasture, common property resources, forest and extent of use of plant biomass for feeding. However, the major challenges in estimating feed-mediated livestock water productivity lies in defining and describing feed resources and feed usage rather than in estimating water depletion. Once feed resources and feed usage are described in sufficient detail, water depletion for livestock feed production can be estimated from, and linked to, climate, irrigation and soil and crop parameters (Fig. 4). The feed database tool as conceived and constructed by NIANP (2003) provides a perfect starting point. It simply needs to be connected and combined with modules that estimate total evapotranspired water per ha of land use. Ideally, feed resources and evapotranspired water should be matched at the smallest common spatial units from which feed databases are built, such as in the NIANP case villages. However, as outlined in Fig. 4, a range of specific crop-management, soil and meteorological data will be required and the spatial availability of these datasets will determine at which spatial level feed resource–water demand datasets can be constructed. The core information generated by the input variables listed in Fig. 4 is total evapotranspiration in mm/day by crop/plant type, which needs to be computed for crop-specific growing period and multiplied by a factor of 10 to get the output in m^3/ha per feed-source type [crop type (compare also van Breugel *et al.* 2010)].

One of the major limitations for the water-requirement calculations remains the availability of good-quality input data. First, the core data on land-use and cropping patterns are limited in many developing countries. Often annual agricultural census data are available by crop type only. The actual crop residue data that goes into the feed database are thus constructed on the basis of harvest indices and other locally developed conversion factors. The data on planted fodder are commonly reported as a percentage of total cropped areas, without details on the fodder crop types and varieties (e.g. Ramachandra *et al.* 2007) and data on productivity are often lacking. In many developing and emerging countries of the world, green fodder from collecting, grazing or natural pasture, fallow lands and

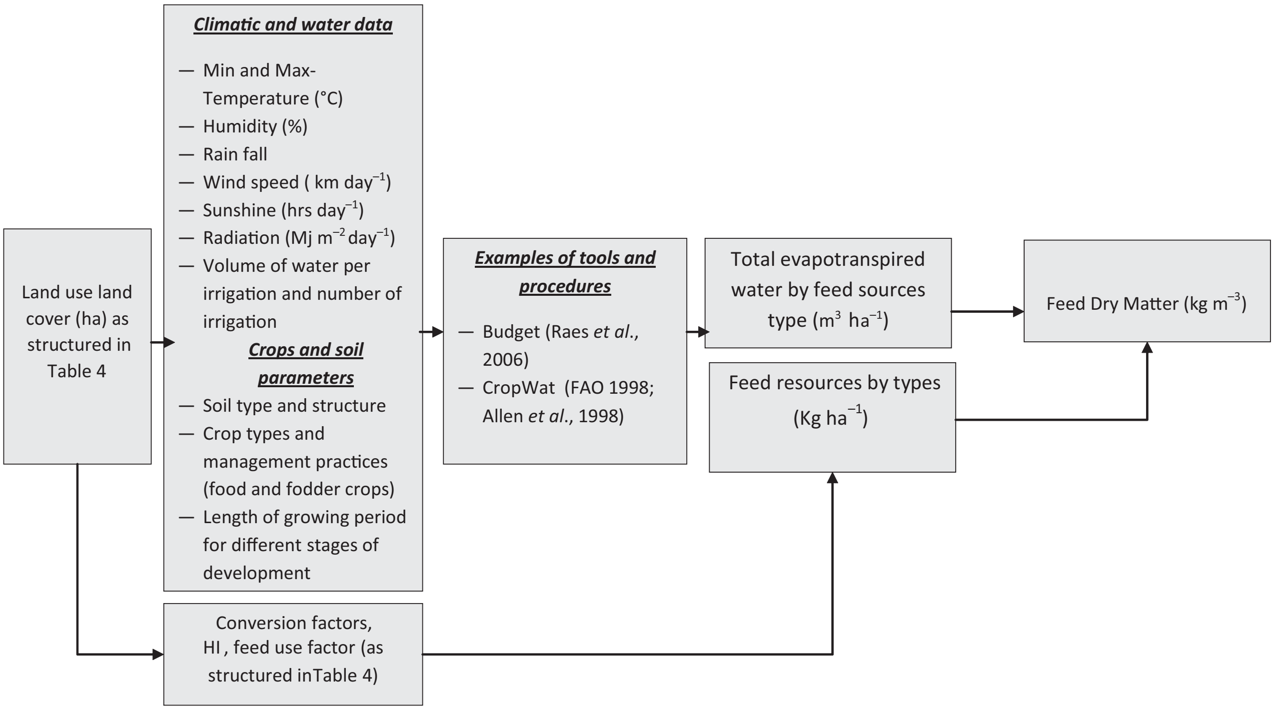

Fig. 4. A simplified framework to combine feed resource database and water-input requirement estimates.

wastelands constitute an important feed resource. Lack of data on species composition, area extent and productivity are thus major gaps in need of being addressed (Ramachandra *et al.* 2007). In addition, the conversion values and harvest index (HI) are dynamic in view of ongoing crop diversification and intensification efforts. In brief, feed database information across countries and regions are inconsistent. Investments in innovative approaches toward estimation and standardisation of such variables are thus of paramount importance.

Once the feed database is established, the actual procedures, specification and tools to process and compute effective rainfall and evapotranspiration are well established (e.g. Allen *et al.* 1998; FAO 1998). As depicted on Fig. 4, data used as input into these tools comprise rainfall and reference evapotranspiration (ET_0) or detailed climatic parameters to compute ET_0. Many countries have a good density of climatic station networks that, with relatively straightforward processing, can provide the necessary input data. There are also a lot of freely available global datasets containing a variety of climate variables. The WorldClim (http://worldclim.org/, accessed 4 July 2014), and CCAFS (http://www.ccafs-climate.org/data/, accessed 4 July 2014) data portals and local climate estimator [LocClim (FAO 2005)], for example, contain information for long-term average, current climate as well as projections for the future. Local relevance and spatial resolution remain important challenges. Cross-checking with the abovementioned climate station data is thus important.

The evaporation power of the atmosphere is expressed by ET_0. The ET_0 represents the evapotranspiration from a standardised vegetated surface. This needs crops specifications, such as crop coefficients, stress resistance factors and rooting depth, which are available also for major crops from Allen *et al.* (1998) or already incorporated into these tools; selection of crop of interest suffices to capture these crop-specific values. Validation of these for the local circumstances will be important.

Soil data are also important input to these tools. CropWat, for example, requires a very simplified soil type in terms of its structure (FAO 1998) to compute soil water. Information such as FAO's global soil map or ISRIC's Harmonised World Soil Database can be also explored to capture such soil information. With increasing information technology and worldwide data networking, the opportunities to use relevant and good-quality global or regional datasets are likely to increase. While the geographical information system tools that enable superimposing these on the administrative or agro-ecological units at which the feed database is collected are already widely available.

Still, concerted action for enhancing livestock water productivity by, for example, linking feed and water resource databases is currently constrained by a lack of both awareness and investments. A conventionally sectorial approach (e.g. feed, water, soil, trees) still dominates, resulting in one-dimensional advice for policy, often with marginal benefit to the development and sustainability agenda. Soft coupling of the water–feed nexus by external models and tools is time consuming, prone to errors and it limits the development of regional and global scenarios from the understanding of local trends. We suggest investing in hard coupling of feed resource databases (e.g. NIANP 2003) with water resource tools (Budget, CropWat), with crop management–soil–meteorological data being the interface between these two modules.

Conclusions

Often unrealised, water requirement for feed production is the major taker of water in livestock production, surpassing drinking water requirements by 100-fold and more. With strongly increasing demand for animal-sourced food in developing and emerging countries, more feed will be required, but this feed needs to be produced in a more water-use-efficient way than is currently the case. By-product feeding based on improved basal feed ingredients and well targeted supplementation will reduce water requirements relative to animal produce. Linked intensification of crop and livestock production will be a major driver for higher feed-mediated WUE in livestock production. To mainstream improvement in WUE of feed resourcing and feeding, feed resource databases should be combined with crop–soil–meteorological data to calculate how much water is required to produce the feed at the available smallest spatial scale of crop–soil–meteorological data availability. A framework is presented of how such a tool can be constructed from secondary datasets on land use, cropping patterns and spatially explicit crop–soil–meteorological datasets.

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