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PERSPECTIVES ON ANIMAL BIOSCIENCES

Net protein contribution from an intensive Australian pork supply chain

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ABSTRACT

Debate surrounding the adverse consequences of feeding human-edible feedstuffs to livestock can be addressed through calculation of the net protein contribution (NPC) of the production system. If the NPC is greater than 1.0 for the production system, then there are net benefits from the system for human populations with an ever-increasing requirement for protein and amino acids. The aim of this paper was to calculate the NPC for an Australian pork supply chain on the basis of the unique characteristics of Australian ingredients. While calculation of NPC is not complex, intimate knowledge of the source of the nutrients and their quality, and interpretation of their human-edible protein fractions is essential if an accurate estimate is to be achieved. The NPC for an Australian pork supply chain was calculated using (a) actual, published or estimated values for human-edible fractions of feedstuffs, (b) the percentage of protein available within raw materials considered to be human edible, (c) recommended amino acid scoring patterns for infants, adolescents and adults, (d) published, and calculated from standard reference nutrient databases, digestible indispensable amino acid scores, (e) carcase yields and carcase composition from published studies, and (f) actual feed formulations, feed volumes and production data from a large Australian pork supply chain. The NPC for the assessed Australian pork supply chain was 3.26. This means the supply chain generates more than three times the human-edible protein it consumes in the process. This NPC is higher than previously published values, largely because of the composition of Australian pig diets, but demonstrates the positive value that livestock production systems make to human food supply. Livestock systems are often targeted as net consumers of vital nutrients such as protein and amino acids and the diversion of these nutrients from human diets. If production systems focus on the utilisation of waste streams, co-products and human-inedible feedstuffs, then they can make a net contribution to human-edible protein supply.

Keywords: animal nutrition, carcass composition, digestibility, feed quality, net protein contribution, pigs, proteins, pork quality, sustainability indicators.

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Introduction

With an increasing demand on our agricultural resources, it is imperative that all food production systems are making a net contribution to food supply, particularly livestock systems that in some cases consume nutrients that could otherwise be fed directly to humans. Current food consumption patterns indicate that 70% more food will need to be produced by 2050 (FAO 2018) from available land resources that have recently peaked (Taylor and Rising 2021). This is also the case for meat, with meat consumption expected to increase by 50% by 2050 (FAO 2018).

The significant challenges confronting our food systems have turned the focus increasingly to their respective sustainability. Often, popular commentary purports the virtues of plant-based protein over animal-based protein as being more sustainable. For the most part, these comparisons are based on environmental impacts or life-cycle assessments (LCA) of various foodstuffs that typically use single-score comparisons based on water, energy, greenhouse-gas emission-intensity, land-use and land use-change parameters. Whereas it is generally agreed that plant-based food stuffs have lower greenhouse-gas emissions than do animal food stuffs, there has been much discussion about the appropriateness of current LCA comparisons between plant- and animal-based proteins, with variations in methodology making it difficult to achieve an accurate comparison. Also, meals are eaten rather than individual foodstuffs and the gap in GHG emissions from a pork meal and a vegetarian meal is not as big as current commentary would suggest (Davis *et al.* 2010). Most reported LCA studies comparing meat and plant protein foodstuffs do not account for the GHG emissions for the waste proportion of feedstuffs (production/manufacture, retail and household), with considerably higher waste attributed to plant foodstuffs (Conrad *et al.* 2018).

As society developed, livestock systems thrived by producing nutrient-rich food from low-value inputs that were not used for human consumption, together with a myriad of co-products that can be used for shelter, clothing, cooking and health. In the case of ruminants, inedible fodder from generally non-arable land was the primary input, while for monogastric animals, this was undesired human food by-products, excess grain that could not be stored, dairy co-products and milling-waste streams. In modern times, livestock systems have become increasingly reliant on feed crops grown on arable land, either to change the properties of the meat products for more premium markets (as is the case with feedlot Wagyu and Hanwoo beef, Greenwood 2021), or to improve efficiency and reduce cost of production, particularly for intensively reared monogastric animals (Zampiga *et al.* 2021). This is argued to increase the feed-food competition, as arable land is being diverted to produce a lower quantity of food from livestock production, thereby further affecting the global supply of food (Schader *et al.* 2015). The use of human-edible food in livestock accounts for one-third of global grain production (Mottet *et al.* 2017), with projections of the growth in cereal grain use as livestock feed of 1.4% per annum (CAST 1999), whereas almost two-thirds of protein in the diets of pigs and poultry in northern Europe is derived from human-edible feedstuffs (Wilkinson 2011). What this argument overlooks is the amount of edible grain from arable land that does not meet human food standards, and hence needs to be disposed of elsewhere, nor does it measure the comparative nutritive value of grain versus animal products for humans. Regardless, the sustainability and net food contribution from livestock systems is in the spotlight and needs to be addressed.

Numerous strategies to increase sustainability in livestock production have been suggested, and these generally fall into the following three categories (Schader *et al.* 2015):

1. Efficiency strategies: productivity increases, aiming to meet expected demand while curbing environmental impacts.
2. Sufficiency strategies: reduced demand for animal products.
3. Consistency strategies: reduction of the use of food-competing components (aka human-edible protein/energy) in livestock diets, which also affects the availability of livestock products.

In reality, it is not one of these strategies that will make livestock production more sustainable, but a combination of all three; production systems need to be efficient with minimal environmental impacts, where possible the systems should be utilising feed components that are not utilised directly by humans, and there should be a more equitable distribution of livestock products for consumers worldwide (as opposed to distribution for the more affluent nations, which arguably need to consume less). Of all three, it is the consistency strategy that also moves the focus from livestock's role as a source of high-quality protein within the food system, to another role, which is utilising resources that cannot be otherwise used for human food production. These resources are (1) grasslands, areas covering approximately two-thirds of the global agricultural area that are less suitable for arable crop production but suited for food production via ruminants, and (2) excess grain that cannot be stored, downgraded grains that are not suitable for human food or processing, food waste and by-products/co-products of food production, such as brans, whey, and oilseed cakes/meals. In addition, while many plant-based proponents are targeting livestock production as being unsustainable, 1 in 12 people still go hungry, and one-third of all food produced is lost or wasted, which equates to ~1.3 billion tonnes of food per year (FAO 2021).

To progress the discussion on the contribution that the respective plant or animal production systems make to the human food chain, and their relative sustainability, the comparison beyond consumption of feed or food stock from arable land to the contribution of the production systems to the nutrient requirements of the human population needs to be elevated, with a key focus being protein and amino acid supply. While an obvious solution would be to simply divert human-edible feedstuffs to direct human consumption, all proteins are not the same, varying in their nutritional profile, digestibility and bioavailability, environmental implications and consumer acceptance. In contrast to most plant proteins, animal proteins are of higher quality and are a complete source of indispensable amino acids (IAA) for humans (Ertl *et al.* 2016*a*). Food is also more than just a nutrient supply, and the social motivations for the consumption of animal protein, including pleasure, luxury, and indication of social status, are powerful and difficult to alter (Wyngaarden *et al.* 2020).

Net protein contribution (NPC) describes the contribution of a production system to meeting human nutritional requirements. If the NPC is greater than 1.0, the system is a net contributor, producing more protein than is being consumed during production. If it is below 1.0, the production system is not contributing positively and competing for protein with human nutritional requirements (Ertl *et al.* 2016*b*). To determine NPC of a livestock production system, the attributes of the protein and its quality, the efficiency of protein conversion in the animal and the contribution it makes to meeting the nutrient requirements of the consumer need to be understood.

Dietary protein quality is primarily characterised by the content of IAA. Indispensable amino acids cannot be synthesised by the human body and must be obtained from the diet (Herreman *et al.* 2020). The digestible indispensable amino acid score (DIAAS) is the current recommended standard to evaluate the nutritional quality of proteins (FAO 2011), and recommends the classification of proteins by using quality categories based on the DIAAS value, as follows: <75 (no quality claim); 75–99 (high-quality protein); and ≥100 (excellent-quality protein). Most cereals, legumes and forages have proteins of low nutritional quality, soybeans are considered high-quality protein, whereas potato protein and animal protein such as eggs, milk, meat and their derivatives are sources of excellent-quality protein. Animals can convert low-quality protein and store these nutrients that would otherwise be inaccessible or lost to the agri-food system and make them nutritionally accessible to humans (Wyngaarden *et al.* 2020).

The most obvious and classical way of measuring the efficiency of the conversion of feed to food is through a feed conversion ratio (FCR), which simply indicates the amount of feed consumed by the animal for each unit of liveweight it gains. Monogastric species (pigs and broiler chickens) convert feed more efficiently than do ruminants, with ruminants fed diets higher in grain content converting more efficiently than those consuming just forages. A lower FCR is often translated as being a smaller burden on the environment; however, land usage and the alternative uses of feedstuffs should also be considered (Peters *et al.* 2014).

If we consider the alternative uses for feedstuffs, in particular those suitable for humans, then conversion ratios can look very different, leading to different interpretations. On the basis of global estimates of meat production and feed use, Galloway *et al.* (2007) calculated the 'total feed to meat' ratio in ruminant and monogastric systems to be 20:1 and 3.8:1 respectively. However, when they adjusted the data to include only 'feeds from arable land', the ratios shifted to 3:1 and 3.4:1 respectively. This knowledge has led people to consider the human-edible protein conversion efficiency (HePCE) as a comparator of food systems. Others have continued this refinement by considering the quality of protein being consumed, and subsequently produced, resulting in being able to define the NPC of a food.

The reported NPC studies for livestock are limited to a handful of studies mainly conducted in Europe, which is in sharp contrast to LCA studies reported for various foodstuffs. In Australia, there has only been one reported NPC study for beef from rangeland and feedlot systems (Thomas *et al.* 2021). This paper describes the process for calculating NPC and then applies the methodology to calculate the NPC from an intensive pork supply chain in Australia.

Calculating net protein contribution

The NPC describes the contribution of a production system to meeting human nutritional needs (Ertl *et al.* 2016*b*). The NPC is calculated in several steps that consider the efficiency of turning human-edible feed into human-edible protein and the quality of the protein fed.

The first step is the calculation of the human-edible protein conversion efficiency (HePCE), the ratio of human-edible protein produced (HePp) and human-edible protein consumed (HePf).

$$\mathrm{HePCE} = \frac{\mathrm{HePp}}{\mathrm{HePf}}$$

As not all proteins are created equal, in terms of amino acid composition and ratio, the second step is to consider the ratio of the quality of the protein (PQR) that is being produced (DIAASp) and the quality of the protein being fed (DIAASf).

$$\mathrm{PQR} = \frac{\mathrm{DIAASp}}{\mathrm{DIAASf}}$$

The third, and final, step is the multiplication of the efficiency of human-edible protein conversion (HePCE) by the change in protein quality (PQR) that occurs when this human-edible protein is fed to animals. This is the net protein contribution (NPC) of the system being examined.

$$\mathrm{NPC} = \mathrm{PQR} \times \mathrm{HePCE}$$

Although these three equations seem straightforward, there is considerable complexity and interpretation involved in determining the amount of human-edible protein and its quality.

Human-edible protein determination – feed (HePf)

When it comes to the definition of the 'human-edible' fraction of a raw material, differences among authors show that estimation methodology is not clear and consistent (Laisse *et al.* 2016). The Council for Agricultural Science and Technology (CAST 1999) calculated estimates of the proportions of human-edible energy and protein in feedstuffs without providing any methodology behind their estimates. Wilkinson (2011) reportedly expanded these CAST (1999) proportions to broader categories, and assumed that 80% of cereal, pulse grains and soybean meal were edible for humans, while only 20% of other oilseed meals and by-products of all other grains were edible. The term human-digestible protein (HDP) is also used.

Determining an accurate measure of the potential human-edible protein of feedstuffs is difficult, as the human-edible fraction of raw materials is not one fixed and generally applicable value, but differs from region to region. It depends on the technology available to, potentially, transform the food, as well as the degree of food availability, and the eating habits of consumers (Laisse *et al.* 2016). A good example of this is bread wheat entering a flour mill. If wholemeal bread is being produced, then the human-edible proportion is close to 100%, falling to 85% for brown bread and 70% for white bread (Wilkinson 2011). Ertl *et al.* (2015) took this into account by looking at the scientific literature to support the following three scenarios for estimating the human-edible fraction (Table 1):

- Low: recovery of human-edible energy and protein from feedstuffs is lower than described on average in the literature. These recovery rates can be seen as easily achievable without high-end technology and/or representing above-average processing losses.
- Medium: this scenario describes the most likely achievable human-edible fraction for protein and energy with current standard technology.
- High: for this scenario, relatively high extraction rates are achieved due to implementation of some kind of sophisticated technology or a moderate change in eating habits (e.g. increasing the consumption of whole-grain foods).

Similarly, Laisse *et al.* (2016) looked at industrial processes used in France to produce food from plant products. The proportion of human-edible protein corresponded to the ratio of the amount of protein actually edible and used in human food after processing to the total protein of the raw material prior to processing. This study also looked at potential scenarios based on strong growth in protein demand, which would lead to greater enhancement of the value of plant proteins, increasing the competition between animal and human consumption and changing eating habits. Estimates for the human-edible fraction of a range of raw materials are shown in Table 2, including our estimates for human-edible fractions of feedstuffs for Australia used in the calculations presented in this paper. A key difference between Australian and overseas values is the fact the Australian pork industry utilises processed animal proteins (PAPs) that are notable omissions from most pig diets in Europe and to some extent in North America. It should be noted that the higher the human-edible fraction within a raw material, the harder it will be for the livestock system to make a positive NPC. To this end, the values attributed for the calculations in this paper could be considered conservative, and over time, more knowledge of the ingredient source could allow us to yield a higher NPC from pork production.

Determining the human-edible protein in feed is clearly complicated by social, cultural, and regional specifics. These influence the assumptions that are made; therefore, results need to be interpreted carefully and comparisons among production systems made with caution. Values attributed to ingredient inputs into the supply chain being assessed in this paper take into account the actual end uses historically, now and in the future. For example, barley has been attributed a value of 60% (which is not inconsistent with other estimates) on the basis that the supply chain seeks parcels of grain that have not made malting specifications or are weather-damaged. Very little sorghum is used for human consumption in Australia, downgraded parcels are sought for diets, and it has an important role as a rotation crop with other more human-edible cereals (the same applies to faba beans grown in Queensland). Soybean meal is more contentious, with some contending that soybeans are grown as much for the meal as a livestock feed as they are for oil for human food (Goldsmith 2008). With vegetable-oil pricing now heavily influenced by US renewable energy mandates, the meal is more and more becoming a by-product (supply exceeding demand for human consumption only, Lusk 2022), so a conservative position of 50% has been adopted.

Meat and bone meal (MBM), as with most PAPs, is not considered to be edible by humans and therefore is given a zero value. Although human-edible protein may have been utilised in the production of PAPs, an approach similar to the allocation of GHG emissions to the primary product when MBM is being utilised as a renewable-energy source (Ariyaratne *et al.* 2015; Kowalski *et al.* 2021) has been applied. If economic allocation is utilised, Beer *et al.* (2007) showed that MBM comprised just 0.55% of the total economic value of the beef supply chain in the year 2000. If we included MBM at this 0.55% level, it would increase the total human-edible protein fed by 0.18%.

Table 1. Estimation of human-edible fractions of feedstuffs (from Ertl *et al.* (2015)).

Feedstuff	Basis for estimating the human-edible fraction
Wheat	Milling grade depending on type of flour (fine flour–whole-grain flour)
Barley	Milling grade depending on type of flour (pearls–dehulled grain flour)
Maize	Possible nutrient extraction rates or milling grade
Triticale	Similar nutrient composition and qualities as wheat = >calculated in wheat equivalents
Rye	Milling grade depending on type of flour (fine flour–whole-grain flour)
Wheat bran	High fibre content of wheat bran increases faecal energy losses, thus amounts for human consumption are limited
Peas	Possible protein and starch extraction or dehulled whole peas
Soybeans	Possible protein and fat extraction (concentrates/isolates) or dehulled whole beans
Soybean/sunflower/rapeseed cake and meal	Possible protein (and fat) extraction rate
Maize silage	Potential starch extraction at different maturity stages or harvested as maize grains

Table 2. Estimates of the percentage of protein available within raw materials considered to be human edible.

Raw material	CAST (1999)	Wilkinson (2011)	Estimates of human-edible protein (%)							Hennessy et al. (2021)	Current paper
			Ertl et al. (2015); Ertl et al. (2016a)			Laisse et al. (2016)		Laisse et al. (2018a)			
			Low[A]	Med	High	Act[B]	Pot	Act	Pot		
Cereals and cereal by-products											
Barley	60	80	40	65	80	87	92	61	66	61	60
Maize, grain	60	80	70	80	90	15	32	15	30	15	80
Oats	70	80	50		75	84	94			80	80
Rice										80	80
Rye			60	80	100			72	80		80
Sorghum	60										20
Triticale		80	60	80	100	0	84	72	80		0
Wheat		80	60	80	100	67	75	66	74	66	80
Wheat, bran/millrun	0	20	0	10	20	98	98	90	98		20
DDGS wheat/barley		0		0		0	0				0
Gluten – corn		0				0	0				20
Gluten – wheat			0		80			100	100		20
Other grains			51		82						
Oilseeds and oilseed by-products											
Cottonseed cake	0		63		80						0
Flax seed cake			5		19						0
Linseed		80				40	79				40
Rapeseed			30		87			0	27	59	0
Rapeseed meal		20	30	59	87	0	55				0
Rapeseed cake			30	59	87			0	55		0
Sunflower			14		46						80
Sunflower meal		20	14	30	46	0	55				0
Sunflower cake			14	30	46			0	55		0
Other oilseed cakes			27		52						0
Other oilseeds			28		68						0
Soybean meal	70	80	50	71	92	60	90				50
Soybean cake			80	71	92			60	90		0
Soybeans		80	50	92	93			61	76	61	80
Plant proteins											
Field beans		80	70		90	92	98	92	95	95	80
Palm-kernal cake			50		80						0
Peas		80	70	80	90	76	91	74	92		80
Potato-protein feed		0	0		80					90	0
Potatoes			0		80	0	0				80
Other pulses			63		81						80
Molasses (beets)			0		80			80	80		0
Sugarbeet pulp		0		0		0	0	0	0		0
Fodder	0	0		0		0	0	0	0		0
Lucerne, dry		0		0		0	30	0	30		0

(*Continued on next page*)

Table 2. (*Continued*).

Raw material	CAST (1999)	Wilkinson (2011)	Estimates of human-edible protein (%)							Hennessy *et al.* (2021)	Current paper
			Ertl *et al.* (2015); Ertl *et al.* (2016*a*)			Laisse *et al.* (2016)		Laisse *et al.* (2018*a*)			
			Low[A]	Med	High	Act[B]	Pot	Act	Pot		
Maize, silage		0	19	29	45	11	23	10	20		0
Maize, whole plant			19		45						0
Milk and milk by-products											
Whole milk, fluid			30		50					100	80
Skimmed milk, fluid			0		80						80
Whey, fluid			0		80			80	94		80
Processed animal proteins											
Fish meal			0		80						0
Meat meal	0										0

[A]Estimates under different technology/processing capabilities. Low, below average; Med, current technology; High, future technology to improve utilisation.
[B]Act, currently realised; Pot, potential with new technology for a greater valorisation of plant proteins.

Human-edible protein determination – produced (HePp)

The amount of edible protein produced can be used to assess the efficiency of different production systems, allowing comparison among dairy, egg and meat production. When it comes to the definition of edible fractions, some production systems are easy to define, the edible fraction of milk and eggs is almost 100%, but meat production is more complex.

Large differences in yield exist among the species themselves on multiple levels. The primary step of slaughtering an animal is the production of a carcase, where offal, some fats and inedible products are removed. When compared with the liveweight of the animal, this dressing percentage has a large range among species, from 40% for fish to 75% for pork (Nijdam *et al.* 2012), whereas the yield of retail cuts from these carcases varies less, 70% for beef to 100% for fish. However, if we multiply these numbers through to a lean meat yield of the live animal, only approximately one-third of a live ruminant makes it onto the consumers table, compared with roughly 56% of a pig or a bird (Table 3).

A large component of meat and other animal protein consumption is cultural (Chiles and Fitzgerald 2018), with consumption of different species and their components having long historical origins. Therefore, the definition of the 'edible' fraction differs among countries, and among population groups within a country (Flachowsky *et al.* 2017). Pork production does not produce only meat, with a not insignificant contribution of edible offal from the 'fifth quarter' contributing to human nutrition in many diverse markets. Although consumption of this 'fifth quarter' is often low domestically within western countries, significant export opportunities exist into communities where nose-to-tail consumption is the norm, not a novelty. Edible-offal estimates range from 2.4% to 8.0% of the live market pig (Table 4).

The final component to calculating the human-edible protein of pork is determining the protein content of the pork products. There are various sources (Table 5) that have determined values for pork products. An intact pork carcase, the simplest pork product, ranges in value from 114 to 173 g protein/kg (CAST 1999; Schinckel *et al.* 2001; Ertl *et al.* 2016*a*). We could further refine this to the meat produced, which would allow us to use a protein content of 215 g/kg (Laisse *et al.* 2018*b*); however, we would also need to accurately determine the meat yield of a pork carcase. Offal has also been similarly defined, with Seong *et al.* (2014) determining the protein content of individual organs. The intestines were the lowest, with 85 g/kg for large intestine, 120 g/kg for the small intestine, with the pancreas (210 g/kg) and the liver (221 g/kg) being the highest. If all the fancy meats (heart, liver, kidney, tongue) are grouped together, then the protein content ranges from 151 to 181 g/kg (Ertl *et al.* 2016*a*; Laisse *et al.* 2018*b*). For the purpose of the calculation reported in this paper, we have estimated the protein content for the carcase and offal to be 140 g/kg and 180 g/kg respectively, on the basis of the ranges in the reviewed literature (Table 5).

Table 3. The yields of carcase (dressing percentage), retail meat yield of the carcase and the lean meat yield of liveweight of different meat production systems (from Nijdam *et al.* (2012)).

Item	Beef	Mutton	Poultry	Fish	Pork
Dressing percentage	53	46	70	40	75
Retail meat yield of carcass (%)	70	75	80	100	75
Lean meat yield (%)	37.0	34.5	56.0	40.0	56.3

Table 4. Composition (% of liveweight) of a market pig.

Item	Carcase	Meat	Fat	Rind	Bone	Edible offal	Blood	Pet food	Inedible offal	Waste
Ockerman and Hansen (2000)										
Denmark	75–80									
Sweden	69		3			7	3			11
USA-1	56		16			4	4			6
USA-2	56		16	2.7		2.4	3			12
Ertl *et al.* (2016*a*)					12	2.65	2	8.5		9
Laisse *et al.* (2018*a*)	78	45								
Laisse *et al.* (2018*b*)	78	45	21		9	8			14	
Dourmad *et al.* (2015)	78	46.0	17.9	4.7	8.5	3.5	3.5		4.5	8.9
Schinckel *et al.* (2001)										
Light weight (83.9 kg)	74.7	43.9	37.2							
Heavy weight (97.4 kg)	75.5	42.6	39.2							

Digestible indispensable amino acid score

The match between dietary supply and human protein needs is vital to support the health and wellbeing of human populations (FAO 2011). Feeding the world's growing population in a time when constraints on land, water and food resources are increasing, requires an accurate method to define the amount and quality of protein required to meet human nutritional needs. Over 30 years ago, a joint FAO/WHO expert group recommended the use of the protein digestibility corrected amino acid score (PDCAAS) for evaluating protein quality.

In calculating the PDCAAS, the limiting amino acid score (the ratio of the first-limiting amino acid in a gram of the target food protein to that of the reference protein) is multiplied by protein digestibility, with the aim to assess how well the dietary protein can match the amino acid demand. Many reviews were undertaken by stakeholders that raised concerns and limitations of the PDCAAS method, and after 20 years of use, a new expert panel was established to address these concerns, the major criticisms being as follows (FAO 2011):

- The PDCAAS method does not credit extra nutritional value to high-quality proteins (i.e. those that supply amino acids above requirements are truncated to 100).
- The PDCAAS method overestimates protein quality of products containing antinutritional factors.
- The PDCAAS method does not adequately take into account the bioavailability of amino acids.
- The PDCAAS method overestimates the quality of poorly digestible proteins supplemented with limiting amino acids, and of proteins co-limiting in more than one amino acid.

The result of this expert consultation was the establishment of a new protein-quality measure, the digestible indispensable amino acid score (DIAAS). As protein digestibility does not always reflect the digestibility of individual dietary IAAs, using a score based on the individual dietary IAA digestibility is preferable, and is defined as

$$\text{DIAAS}\ \% = 100 \times \left(\frac{\text{mg of digestible dietary indispensable amino acid in } 1 \text{ g of the dietary protein}}{\text{mg of the same dietary indispensable amino acid in } 1 \text{ g of the reference protein}} \right)$$

Digestibility should be based on the true ileal digestibility (i.e. determined at the end of the small intestine) of each amino acid, preferably determined in humans, or, if not possible, in the growing pig or in the growing rat, in that order. The panel recognised that amino acid digestibility may vary greatly among batches of food or food ingredients and that it is impractical to assay individual batches, such that the use of tabulated data is permitted.

The panel also established recommended amino acid scoring patterns (i.e. the reference protein) to be used for calculating protein quality for dietary assessment (Table 6):

- Infants (birth to 6 months), the pattern of breast milk.
- Young children (6 months – 3 years), the pattern for the 0.5-year-old infant.

Table 5. Yield (% of liveweight), protein and energy content of pork products and by-products.

Item	Yield (%)	Protein content (g/kg)	Energy content (MJ/kg)	Energy content (g/kg)	Carcase weight (kg)	Fat depth (mm)
CAST (1999)						
Carcase		114	12.9	287		
Ertl et al. (2016a)						
Carcase	70.5	139	16.84			
Blood	2.0	185	4.29			
Fancy meats[A]	2.65	181	5.94			
Total by-products	12.0	148	13.99			
Edible kill fat	2.4	0	32.09			
Herrero et al. (2013)						
All products		106				
Laisse et al. (2018b)						
Meat	45.0	215				
Rind and fats	21.0	128				
Bone (gelatin)	9.0	110				
Consumable offal[B]	8.0	151				
Laisse et al. (2018a)						
Carcase and offal		158	11.8			
Liu et al. (2021)						
Whole body composition – male	78.3	149		160	84.9	12.8
Whole body composition – female	78.8	144		184	85.7	13.0
Schinckel et al. (2001)						
Light carcase (83.9 kg)	74.7	173		373	83.9	26.5
Heavy carcase (97.4 kg)	75.5	166		397	97.4	29.8
Seong et al. (2014)						
Heart	0.33	176	7.15			
Liver	1.35	221	7.74			
Lung	0.53	166	5.68			
Stomach	0.56	171	5.93			
Small intestine	0.86	120	4.75			
Large intestine	0.90	85	10.88			
Spleen	0.16	178	5.37			
Uterus	0.42	151	4.76			
Pancreas	0.18	210	8.02			
Current paper						
Carcase	76.5	140				
Edible offal	4.74	180				

[A]Heart, liver, kidney and tongue.
[B]Heart, liver, kidneys, certain white offal, edible blood, part of hoofs.

- Older children, adolescents and adults, the pattern for 3- to 10-year-old children.

In effect, only two of these scoring patterns were used, namely (1) the infant pattern for the regulatory assessment of infant formulas, and (2) the young children pattern for the regulatory assessment of all other foods and population groups. The ratio is calculated for each individual amino acid and the lowest value is designated at the DIAAS and used as an indicator of dietary-protein quality. Independent of the absolute variation in DIAAS among raw materials that can be observed (Table 7), the dataset shows clear disparity within plant proteins.

Table 6. Recommended amino acid scoring patterns for infants, children and older children, adolescents and adults to be used in the calculation of DIAAS (FAO 2011).

Age group	His	Ile	Leu	Lys	SAA	AAA	Thr	Trp	Val
	(mg/g protein requirement)								
Infant (birth to 6 months)[A]	21	55	96	69	33	94	44	17.0	55
Child (6 months – 3 years)	20	32	66	57	27	52	31	8.5	43
Older child, adolescent, adult	16	30	61	48	23	41	25	6.6	40

SAA, sulfur amino acids – methionine + cysteine; AAA, aromatic amino acids – phenylalanine + tyrosine; His, histidine; Ile, isoleucine; Leu, leucine; Lys, lysine; Thr, threonine; Trp, tryptophan; Val, valine.
[A]Infant is based on the gross amino acid content of human milk.

Table 7. Digestible indispensable amino acid score (DIAAS) and first limiting amino acid of various raw materials as cited in publications or calculated from standard reference databases.

Raw material	DIAAS (first limiting AA)				
	Publications			Calculated	
	Ertl *et al.* (2016*a*, 2016*b*)	Mathai *et al.* (2017)	Herreman *et al.* (2020)	INRAE-CIRAD-AFZ	NRC (2012)
Cereals and cereal by-products					
Barley	47.2			50 (Lys)	59 (Lys)
Corn/maize	42.4		36 (Lys)	44 (Lys)	49 (Lys)
Oats	56.7		57 (Lys)	52 (Lys)	73 (Lys)
Rice			47 (Lys)	57 (Lys)	74 (Lys)
Rye	47.6			50 (Lys)	58 (Lys)
Sorghum				30 (Lys)	36 (Lys)
Triticale	49.8			58 (Lys)	53 (Lys)
Wheat	40.2	45 (Lys)	48 (Lys)	39 (Lys)	44 (Lys)
Wheat bran/middlings	48.8			56 (Lys)	
Corn silage	42.4				
Oilseeds and oilseed by-products					
Canola			72 (Lys)	65 (Lys)	
Rapeseed	70.2		67 (Lys)	67 (Leu)	
Rapeseed expeller	70.2				
Rapeseed cake	70.2			71 (Lys)	
Sunflower	47.8			51 (Lys)	49 (Trp)
Sunflower expeller	49.2			56 (Lys)	
Sunflower cake	46.4				
Soybean	99.6	89 (SAA)	91 (SAA)	87 (SAA)	104 (Val)
Soybean expeller	100.3				97 (SAA)
Soybean cake	97.0				
Soy protein isolate		84 (SAA)		96 (Thr)	84 (SAA)
Plant proteins					
Faba beans	57.0		55 (SAA)	51 (SAA)	61 (SAA)
Hemp			54 (Lys)		
Lupins			68 (SAA)	59 (Trp)	73 (SAA)
Peas	64.7		70 (SAA)	59 (SAA)	
Pea protein concentrate		62 (SAA)		44 (Thr)	
Potato protein concentrate			100	87 (His)	112 (His)

(*Continued on next page*)

Table 7. (*Continued*).

Raw material	DIAAS (first limiting AA)				
	Publications			Calculated	
	Ertl *et al.* (2016*a*, 2016*b*)	Mathai *et al.* (2017)	Herreman *et al.* (2020)	INRAE-CIRAD-AFZ	NRC (2012)
Milk and milk by-products					
Whole milk powder	115.9			110 (SAA)	
Whole milk liquid	115.9				
Skimmed milk powder		105 (SAA)		120 (Val)	115 (SAA)
Skimmed milk liquid	115.9				
Whey			85 (His)	70 (AAA)	86 (His)
Whey protein concentrate		107 (His)			102 (His)
Whey protein isolate		100 (His)			
Casein			117		120 (SAA)
Milk protein concentrate		120 (SAA)			
Sheep milk	109.1				
Goat milk	123.5				
Animal products					
Eggs	116.4		101		
Beef	111.6/109.3				
Chicken	108.2				
Lamb	116.8				
Pork	113.9		117		
Gelatin			2 (Trp)		
Meat and bone meal					61 (Trp)

As the calculation of DIAAS values is dependent on both amino acid content and digestibility within a food stuff, it is therefore subject to variation. Herreman *et al.* (2020) assessed the DIAAS of five animal- and 12 plant-protein sources where multiple datasets existed on IAA composition, crude protein content and IAA standardised ileal digestibility. When assessing the generated DIAAS value from each dataset, different datasets of the same food item fell across multiple quality categories. For consistency, the use of standard reference databases such as the USDA National Nutrient Database (https://fdc.nal.sda.gocv/ndb/), feed ingredient compositions from the Nutrient Requirements of Swine (NRC 2012) or INRAE-CIRAD-AFZ feed tables (https://www.feedtables.com) should allow for consistent values.

Whereas the DIAAS values are obtained from analysis of single protein materials, meals for humans and diets for livestock are often complex, combining raw materials with amino acid profiles that work in complement. Cereal grains are generally high in the sulfur amino acids but low in lysine, but can be combined with leguminous proteins that are generally higher in lysine, but lower in methionine and cysteine, increasing the DIAAS values of the mix. The calculation of a DIAAS for a diet of mixed ingredients is possible given that the quantities of each ingredient are known. The methodology (FAO 2011) utilises the individual raw material IAA composition and digestibility and their inclusion rate in the diet to calculate the true digestible IAA content of the mix to determine its DIAAS value. However, no account can be taken for any changes in digestibility of individual ingredients that may arise from any complementary combinations or antagonistic interactions.

Net protein contribution for pork

The NPC from an Australian intensive pork supply chain is presented in Table 8. The data used for these analyses were based on diet formulations, production and slaughter data from July 2021 until June 2022. The NPC for an intensive Australian pork supply chain is estimated to be 3.26, with this value being higher than the pork estimates reported in the literature (Table 9). This higher NPC for Australian pork is both a factor of a higher HePCE and PQR. Although there is some variance in the estimated percentage of human-edible protein available within raw materials, as a result of regional differences, which are important to consider in assessing environmental impacts (Rodríguez *et al.* 2014), the greater contributor is the inclusion of alternative raw materials including PAPs such as meat and bone meal, which is a key component of pig diets in Australia, contributing 20%

Table 8. The net protein contribution from an intensive Australian pork supply chain, with the human-edible protein conversion efficiency, protein quality ratio and net protein contribution in bold.

Item	Pork
Total annual carcase weight (kg)	88 080 878
Total annual offal weight (kg)	3 951 213
Carcase protein content (g/kg)	140
Offal protein content (g/kg)	180
Human-edible protein produced (HePp[A], g)	13 042 541 328
Human-edible protein fed (HePf, g)	18 653 955 545
Human-edible protein conversion efficiency (HePCE[B], g/g)	**0.70**
DIAAS pork (Ertl *et al.* 2016*a*)	113.9
DIAAS diet (from DIAAS calculation sheets (FAO 2011))	24.4
Protein quality ratio (PQR, DIAAS pork ÷ DIAAS diet)	**4.66**
Net protein contribution (HePCE × PQR)	**3.26**

[A]HePp, sum of Total annual carcase weight multiplied by Carcase protein content and Total annual offal weight multiplied by Offal protein content.
[B]HePCE, Human-edible protein produced divided by Human-edible protein fed.

of all digestible protein in the studied supply chain, and is not considered to be human edible. The largest contributors of human-edible protein to diets in this supply chain were of cereal grain (68.2%) and legume (30.6%) origin; however, they accounted only for 63.1% of all digestible protein. The NPC for Australian pork also compares favourably to that reported for other livestock industries, with the exception of Australian grass-fed beef (Thomas *et al.* 2021), which has been reported to have a very high NPC value of 1597 (noting a 100% grass-fed system should technically have an undefined value with zero human-edible protein being fed). As such, this value should be treated with some caution in the overall context of NPC values for livestock.

Food waste into landfill is a considerable issue both from the sheer volumes of food that is dumped into landfill (7.6 million tonnes per annum in Australia; FIAL 2021) and the considerable greenhouse gas emissions that are associated with this waste (17.5 million tonnes CO_2-e per annum, 3.5% of Australia's national emissions; FIAL 2021). The omnivorous nature of the pig enables the recycling of many food-waste streams and also manufacturing by-products in their diets, and it is here that their advantage over broiler production, 'given the huge dependence of the Australian chicken-meat industry on imported, expensive soybean meal' (Selle *et al.* 2023) can see pig production contributing positively to net protein production for human consumption (Laisse *et al.* 2018*b*). It is estimated, for instance, that the French pork sector utilised nearly 1.4 million tonnes of by-products (including oilseed cakes and distillers' grains) in 2015 in commercial stockfeed manufacturing alone. In addition, many farms manufacturing their own feed also buy meals

Table 9. The net protein contribution for various livestock industries.

Item	Human-edible protein conversion efficiency (g/g)	Protein-quality ratio	Net protein contribution
Ertl *et al.* (2016*a*) – current ingredient technology			
Cattle	1.52	1.84	2.81
Dairy cows	1.98	1.90	3.78
Grower-fattening bulls	0.45	1.66	0.73
Swine	0.36	1.74	0.64
Laying hens	0.63	1.63	1.04
Broiler chickens	0.52	1.43	0.76
Turkeys	0.50	1.11	0.56
Sheep	0.54	1.94	1.04
Goats	0.82	1.86	1.53
Ertl *et al.* (2016*a*) – optimum ingredient technology			
Cattle	0.87	1.84	1.60
Dairy cows	1.11	1.90	2.10
Grower-fattening bulls	0.31	1.66	0.53
Swine	0.29	1.74	0.50
Laying hens	0.36	1.63	0.58
Broiler chickens	0.36	1.43	0.51
Turkeys	0.33	1.11	0.36
Sheep	0.39	1.94	0.75
Goats	0.46	1.86	0.86
Laisse *et al.* (2018*a*)			
Dairy, high production, corn silage			1.01
Dairy, low production, pasture			2.57
Beef, semi-intensive, 17% grain fed			0.71
Beef, pasture, 5% grain fed			0.67
Sheep meat, grassland			1.28
Sheep meat, pasture based, intensive			0.34
Pork, commercial feed mill			1.06
Pork, home mill, corn grain silage			1.23
Broilers			0.88
Layers			1.02
Laisse *et al.* (2018*b*)			

(*Continued on next page*)

Table 9. (*Continued*).

Item	Human-edible protein conversion efficiency (g/g)	Protein-quality ratio	Net protein contribution
Dairy, commercial feed mill, 2011	0.42		0.70
Dairy, commercial feed mill, 2012	0.42		0.76
Dairy, commercial feed mill, 2013	0.42		0.75
Dairy, commercial feed mill, 2014	0.42		1.42
Dairy, home mill, 2014	0.40		1.08
Dairy, commercial feed mill, farm maize, 2014	0.40		1.23
Dairy, home mill, farm maize, 2014	0.40		1.63
Dairy, organic, average years	0.30		0.39
Baber *et al.* (2018)			
Beef, simple feedlot diet, low performance			1.01
Beef, simple feedlot diet, high performance			1.05
Beef, complex feedlot diet, low performance			3.00
Beef, complex feedlot diet, high performance			3.11
Thomas *et al.* (2021)			
Beef, grass-fed, total value chain	689	2.32	1597
Beef, grain-finished, total value chain	0.84	2.32	1.96

and, often liquid by-products to incorporate into diets noting there are significant logistical and biosecurity/health challenges to overcome before these more decentralised food waste streams are readily utilised more widely by the pig industry.

Conclusions

The challenges facing our food systems, with increased demand for food from diminishing resources, the significant amount of food wasted and providing food to the people that need it most, are significant. Whereas the populist commentary constantly questions the livestock industries for environmental damage and competing for valuable food resources affecting the global supply of food, the data suggest that livestock industries can most definitely make a positive contribution to our food systems by utilising by-products/co-products of other food stuffs, and this will continue. The NPC as a measure allows the livestock industries to demonstrate this contribution. The NPC for an Australian intensive pork supply chain clearly demonstrates this positive contribution. The significant amount of food wasted globally provides the pork industries opportunities to further enhance this protein contribution and lower its carbon footprint, provided some of the logistical and health/safety challenges are overcome.

References

Ariyaratne WKH, Melaaen MC, Tokheim L-A (2015) CFD modeling of multi-fuel combustion of coal and meat and bone meal (MBM) in a cement rotary kiln. *International Journal of Modeling and Optimization* **5**, 353–360. doi:10.7763/IJMO.2015.V5.488

Baber JR, Sawyer JE, Wickersham TA (2018) Estimation of human-edible protein conversion efficiency, net protein contribution, and enteric methane production from beef production in the United States. *Translational Animal Science* **2**, 439–450. doi:10.1093/tas/txy086

Beer T, Grant T, Campbell PK (2007) The greenhouse and air quality emissions of biodiesel blends in Australia. Report Number KS54C/1/F2.29. CSIRO, Aspendale VIC, Australia. Available at http://www.cmar.csiro.au/e-print/open/2007/beert_b.pdf [Verified 16 March 2023]

CAST (1999) Animal agriculture and global food supply. Task force report 135. Council for Agricultural Science and Technology, Ames, IA USA.

Chiles RM, Fitzgerald AJ (2018) Why is meat so important in Western history and culture? A genealogical critique of biophysical and political-economic explanations. *Agriculture and Human Values* **35**, 1–17. doi:10.1007/s10460-017-9787-7

Conrad Z, Niles MT, Neher DA, Roy ED, Tichenor NE, Jahns L (2018) Relationship between food waste, diet quality, and environmental sustainability. *PLoS ONE* **13**, e0195405. doi:10.1371/journal.pone.0195405

Davis J, Sonesson U, Baumgartner DU, Nemecek T (2010) Environmental impact of four meals with different protein sources: case studies in Spain and Sweden. *Food Research International* **43**, 1874–1884. doi:10.1016/j.foodres.2009.08.017

Dourmad J-Y, Nassy G, Salaun Y, Riquet J, Lebret B (2015) Estimation des pertes alimentaires dans la filière porcine entre la sortie de l'élevage et la commercialisation des produits. *Innovations Agronomiques* **48**, 115–125.

Ertl P, Klocker H, Hörtenhuber S, Knaus W, Zollitsch W (2015) The net contribution of dairy production to human food supply: the case of Austrian dairy farms. *Agricultural Systems* **137**, 119–125. doi:10.1016/j.agsy.2015.04.004

Ertl P, Steinwidder A, Schönauer M, Schönauer K, Krimberger K, Knaus W, Zollitsch W (2016*a*) Net food production of different livestock: a national analysis for Austria including relative occupation of different land categories. *Die Bodenkultur: Journal of Land Management, Food and Environment* **67**, 91–103. doi:10.1515/boku-2016-0009

Ertl P, Knaus W, Zollitsch W (2016*b*) An approach to including protein quality when assessing the net contribution of livestock to human food supply. *Animal* **10**, 1883–1889. doi:10.1017/S1751731116000902

FAO (2011) Dietary protein quality evaluation in human nutrition. Food and Agriculture Organization of the United Nations, Rome, Italy. Available at http://www.fao.org/ag/humannutrition/35978-02317b979a686a57aa4593304ffc17f06.pdf [Verified 13 January 2022]

FAO (2018) The future of food and agriculture – alternative pathways to 2050. Rome, Italy. Available at https://www.fao.org/global-perspectives-studies/food-agriculture-projections-to-2050/en/ [Verified 22 January 2023]

FAO (2021) The state of food security and nutrition in the world 2021. Food and Agriculture Organization of the United Nations, Rome, Italy. Available at https://www.fao.org/3/cb4474en/cb4474en.pdf [Verified 13 January 2022]

FIAL (2021) The national food waste strategy feasibility study – final report. FIAL – The Food and Agribusiness Growth Centre, Macquarie Park, NSW, Australia. Available at https://www.fial.com.au/sharing-knowledge/food-waste#FSES [Verified 16 March 2023]

Flachowsky G, Meyer U, Südekum K-H (2017) Land use for edible protein of animal origin - a review. *Animals* **7**, 25. doi:10.3390/ani7030025

Galloway JN, Burke M, Bradford GE, Naylor R, Falcon W, Chapagain AK, Gaskell JC, McCullough E, Mooney HA, Oleson KLL, Steinfeld H, Wassenaar T, Smil V (2007) International trade in meat: the tip of the pork chop. *AMBIO: A Journal of the Human Environment* **36**, 622–629. doi:10.1579/0044-7447(2007)36[622:ITIMTT]2.0.CO;2

Goldsmith PD (2008) Economics of soybean production, marketing, and utilization. In 'Soybeans: chemistry, production, processing, and utilization'. (Eds LA Johnson, PJ White, R Galloway) pp. 117–150. (AOCS Press: Urbana, IL, USA)

Greenwood PL (2021) Review: an overview of beef production from pasture and feedlot globally, as demand for beef and the need for sustainable practices increase. *Animal* **15**, 100295. doi:10.1016/j.animal.2021.100295

Hennessy DP, Shalloo L, van Zanten HHE, Schop M, De Boer IJM (2021) The net contribution of livestock to the supply of human edible protein: the case of Ireland. *The Journal of Agricultural Science* **159**, 463–471. doi:10.1017/S0021859621000642

Herreman L, Nommensen P, Pennings B, Laus MC (2020) Comprehensive overview of the quality of plant- and animal-sourced proteins based on the digestible indispensable amino acid score. *Food Science & Nutrition* **8**, 5379–5391. doi:10.1002/fsn3.1809

Herrero M, Havlík P, Valin H, Notenbaert A, Rufino MC, Thornton PK, Blümmel M, Weiss F, Grace D, Obersteiner M (2013) Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences of the United States of America* **110**, 20888–20893. doi:10.1073/pnas.1308149110

Kowalski Z, Muradin M, Kulczycka J, Makara A (2021) Comparative analysis of meat bone meal and meat bone combustion using the life cycle assessment method. *Energies* **14**, 3292. doi:10.3390/en14113292

Laisse S, Rouille B, Baumont R, Peyraud J-L (2016) Évaluation de la contribution nette des systèmes bovins laitiers français à l'approvisionnement alimentaire protéique pour l'être humain. (Evaluation of net contribution of French dairy cattle systems to the protein supply for humans.). *Rencontres autour des Recherches sur les Ruminants* **23**, 263–266.

Laisse S, Baumont R, Dusart L, Gaudré D, Rouillé B, Benoit M, Veysset P, Rémond D, Peyraud J-L (2018*a*) L'efficience nette de conversion des aliments par les animaux d'élevage: une nouvelle approche pour évaluer la contribution de l'élevage à l'alimentation humaine. *INRA Productions Animales* **31**, 269–288. doi:10.20870/productions-animales.2018.31.3.2355

Laisse S, Gaudré D, Salaün Y, Dourmad J-Y (2018*b*) Évaluation de la contribution nette des élevages de porcs en France à la production alimentaire de protéines pour l'homme. [Estimating the net contribution of French pig livestock to the protein supply for humans]. *Journees Recherche Porcine* **50**, 37–42.

Liu F, Brewster CJ, Gilmour SL, Henman DJ, Smits RJ, Luxford BG, Dunshea FR, Pluske JR, Campbell RG (2021) Relationship between energy intake and growth performance and body composition in pigs selected for low backfat thickness. *Journal of Animal Science* **99**, skab32. doi:10.1093/jas/skab342

Lusk JL (2022) Food and fuel: modelling food system wide impacts of increases in demand for soybean oil. Report prepared for the United Soybean Board. Available at https://ag.purdue.edu/cfdas/wp-content/uploads/2022/12/report_soymodel_revised13.pdf [Verified 13 March 2023]

Mathai JK, Liu Y, Stein HH (2017) Values for digestible indispensable amino acid scores (DIAAS) for some dairy and plant proteins may better describe protein quality than values calculated using the concept for protein digestibility-corrected amino acid scores (PDCAAS). *British Journal of Nutrition* **117**, 490–499. doi:10.1017/S0007114517000125

Mottet A, de Haan C, Falcucci A, Tempio G, Opio C, Gerber P (2017) Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. *Global Food Security* **14**, 1–8. doi:10.1016/j.gfs.2017.01.001

Nijdam D, Rood T, Westhoek H (2012) The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. *Food Policy* **37**, 760–770. doi:10.1016/j.foodpol.2012.08.002

NRC (2012) 'Nutrient requirements of swine: eleventh revised edition.' (The National Academies Press: Washington, DC, USA)

Ockerman HW, Hansen CL (2000) 'Animal by-product processing and utilization.' (CRC Press: Boca Raton, FL, USA)

Peters CJ, Picardy JA, Darrouzet-Nardi A, Griffin TS (2014) Feed conversions, ration compositions, and land use efficiencies of major livestock products in US agricultural systems. *Agricultural Systems* **130**, 35–43. doi:10.1016/j.agsy.2014.06.005

Rodríguez C, Ciroth A, Srocka M (2014) The importance of regionalized LCIA in agricultural LCA – new software implementation and case study. In 'Proceedings of the 9th international conference on life cycle assessment in the agri-food sector (LCA Food 2014), 8–10 October 2014, San Francisco CA, USA'. (Eds R Schenck, D Huizen) pp. 1120–1128. (American Center for Life Cycle Assessment: Vashon, WA, USA) Available at https://www.cabdirect.org/cabdirect/abstract/20153221254

Schader C, Muller A, Scialabba NE-H, Hecht J, Isensee A, Erb K-H, Smith P, Makkar HPS, Klocke P, Leiber F, Schwegler P, Stolze M, Niggli U (2015) Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. *Journal of The Royal Society Interface* **12**, 20150891. doi:10.1098/rsif.2015.0891

Schinckel AP, Wagner JR, Forrest JC, Einstein ME (2001) Evaluation of alternative measures of pork carcass composition. *Journal of Animal Science* **79**, 1093–1119. doi:10.2527/2001.7951093x

Selle PH, Macelline SP, Chrystal PV, Liu SY (2023) The challenge to reduce crude protein contents of wheat-based broiler diets. *Animal Production Science*. doi:10.1071/AN22419

Seong PN, Park KM, Cho SH, Kang SM, Kang GH, Park BY, Moon SS, Ba HV (2014) Characterization of edible pork by-products by means of yield and nutrition composition. *Korean Journal for Food Science of Animal Resources* **34**, 297–306. doi:10.5851/kosfa.2014.34.3.297

Taylor CA, Rising J (2021) Tipping point dynamics in global land use. *Environmental Research Letters* **16**, 125012. doi:10.1088/1748-9326/ac3c6d

Thomas DT, Beletse YG, Dominik S, Lehnert SA (2021) Net protein contribution and enteric methane production of pasture and grain-finished beef cattle supply chains. *Animal* **15**, 100392. doi:10.1016/j.animal.2021.100392

Wilkinson JM (2011) Re-defining efficiency of feed use by livestock. *Animal* **5**, 1014–1022. doi:10.1017/S175173111100005X

Wyngaarden SL, Lightburn KK, Martin RC (2020) Optimizing livestock feed provision to improve the efficiency of the agri-food system. *Agroecology and Sustainable Food Systems* **44**, 188–214. doi:10.1080/21683565.2019.1633455

Zampiga M, Calini F, Sirri F (2021) Importance of feed efficiency for sustainable intensification of chicken meat production: implications and role for amino acids, feed enzymes and organic trace minerals. *World's Poultry Science Journal* **77**, 639–659. doi:10.1080/00439339.2021.1959277

Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

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