The net contribution of livestock to the supply of human edible protein: the case of Ireland

D. P. Hennessy[1,2] , L. Shalloo[2], H. H. E. van Zanten[3], M. Schop[1] and I. J. M. De Boer[1]

[1]Animal Production Systems Group, Wageningen University & Research, P.O. Box 338, 6700 AH Wageningen, the Netherlands; [2]Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Fermoy, Co., Cork, Ireland and [3]Farm Systems Ecology Group, Wageningen University & Research, P.O. Box 430, 6700 AK, Wageningen, the Netherlands

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Author for correspondence:
D. P. Hennessy,
E-mail: Donagh.hennessy@teagasc.ie

Abstract

If current food consumption patterns continue, the agriculture sector must provide significantly more food in the coming years from the available land area. Some livestock systems engage in feed–food competition as arable land is used for livestock feed rather than as crops for food; reducing the global supply of food. There is a growing argument that to meet future-food demands sustainably, feed–food competition must be minimized. To this end, we evaluated the effectiveness of two refined metrics to quantify feed–food competition in three livestock systems; dairy and its beef, suckler beef and pig production in Ireland. The metrics are edible protein conversion ratio (EPCR) and the land-use ratio (LUR). The EPCR compares the amount of human digestible protein (HDP) in livestock feed against the amount of HDP the livestock produced, calculating how efficiently it produces HDP. However, the LUR compares the potential HDP from a crop system on the land used to produce the livestock's feed against the HDP the livestock system produced. In both metrics, a value <1 demonstrates an efficient system. The EPCR values for dairy beef (0.22) and suckler beef (0.29) systems consider them efficient producers, whereas pig production (1.51) is inefficient. The LUR values designate that only the dairy beef (0.58) is a net positive producer of HDP from the land used for its feed, with crop production producing more HDP than suckler beef (1.34) and pig production (1.73). Consequently, the LUR can be deemed to be more suitable to represent feed–food competition in livestock production.

Introduction

Today's global food system has a major impact on the environment. It covers over 40% of the global ice and desert-free land, contributes to approximately 25% of anthropogenic greenhouse gas (GHG) emissions, causes one-third of terrestrial acidification and is responsible a significant share of global eutrophication (Poore and Nemecek, 2018; Ramankutty *et al.*, 2018). The livestock sector contributes significantly to these environmental impacts. The sector is responsible for about two-thirds of the food systems' GHG emissions; occupies the majority of all global farmland either as feed or fodder and consumes over 30% of all cereals produced as animal feed (Gerber *et al.*, 2013; Mottet *et al.*, 2017; Poore and Nemecek, 2018). Livestock-related production contributes significantly to the crossing of some planetary boundaries and to the pressure on other planetary boundaries (Campbell *et al.*, 2017; Bowles *et al.*, 2019). Despite this substantial share of agriculture's environmental externalities, livestock only supply 25% of global human digestible protein (HDP) (Mottet *et al.*, 2017). It is clear that the livestock sector has a significant role in agriculture's impact on the environment and we could question if this is in proportion to its share of the food products provided.

If the current food consumption trends continues, the demand for food will increase by 70% over the next 30 years; to secure nutrition demands and bring food production within the planetary boundaries we need to change how we use our livestock systems (Alexandratos and Bruinsma, 2012; Schader *et al.*, 2015). Traditionally, livestock systems were used to create nutrient-rich food from low-opportunity cost biomass (LCB). Ruminants were traditionally used to create food from inedible fodder, whereas monogastrics were fed undesired by-products, such as the residues of potatoes or other types of food-waste (Naylor *et al.*, 2005; Wilkinson, 2011). Current livestock systems do not operate in the same way; instead livestock systems are increasingly reliant on feed crops grown on arable land (Mottet *et al.*, 2017). This engenders feed–food competition as arable land is diverted from crops to produce a lower amount of food from livestock production; reducing the global supply of food (Schader *et al.*, 2015).

Circular agriculture is increasingly observed as a promising way of ensuring a sustainable future-food system (De Boer and van Ittersen, 2018). A core tenet of circular agriculture is to limit feed–food competition. This implies that arable land is used for the production of

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plant biomass for human consumption. Ruminants create nutritional value from grasslands, especially those that are only suitable for the production of forages of one form or another. Farm animals again up-cycle by-products from the production and consumption of plant-source foods into high-quality food (van Zanten *et al.*, 2016). To assess whether a livestock system is engaged in feed–food competition and contributes to a circular food system, there is need to identify or develop accurate metrics to measure feed–food competition.

Several metrics have been developed to measure the net contribution of livestock to the supply of edible protein, such as the edible protein conversion ratio (EPCR) and the land-use ratio (LUR) (Wilkinson, 2011; van Zanten *et al.*, 2016; Laisse *et al.*, 2019). The EPCR compares the amount of HDP in animal feed over the amount of HDP in the animal product (Wilkinson, 2011; Laisse *et al.*, 2019; Mosnier *et al.*, 2021). The LUR compares the potential HDP from a crop grown on the land used to produce the livestock feed against the HDP in that livestock produce (van Zanten *et al.*, 2016). Ertl *et al.* (2016) clearly showed the necessity of including protein quality in the assessment of above-described metrics. Only a single study has used both metrics to assess the net contribution livestock to the human edible protein supply (van Zanten *et al.*, 2016). This study did not consider the fact that the quality of animal-source protein for humans (i.e. amino acid profile) is generally higher than that of plant-based protein. To our knowledge, a consistent analysis of the net contribution of the main livestock systems to the HDP supply using both metrics, adapted for protein quality, is lacking. The aim of this study, therefore, was to assess the net contribution of the main livestock systems to the HDP supply. To this aim, we used Ireland as a case study.

Ireland serves as an interesting case study for three main reasons. First, Ireland's agriculture sector's emissions are dominated by livestock production; specifically, pasture-based ruminant systems (EPA, 2018). Second, over 75% of current arable crops yields are used as animal feed, although this only meets 35% of national feed requirements with feed imported for use in its livestock systems (DAFM, 2018*a*). Third, the quality of the farmland varies; from land wholly suitable for arable crops to marginal grassland on organic peat soils (Gardiner *et al.*, 1980), with the vast majority of the land being not suitable for arable crops.

The three largest livestock sectors by value in Ireland are the ruminants of dairy and beef cattle systems and the monogastric pig system (Bía, 2019). Here, we, therefore, assess the net contribution of these three Irish livestock systems to the net supply of HDP using refined EPCR and LUR in order to include protein quality. Results of this study demonstrate the net contribution of each livestock system to the net HDP supply, and hence their feed–food competition, and as such provides valuable information for future land-use strategies for policy makers.

Materials and methods

In the following sections, we describe or explain the three Irish livestock systems, the computations needed to determine the EPCR, and the computations needed to calculate the LUR. Finally, a sensitivity analysis performed to determine the effects of changing key parameters with high uncertainty is described.

Livestock systems

Dairy production in Ireland is pasture-based, and characterized by spring calving in order to balance pasture yields with feed demand. Replicating the boundaries used in van Zanten *et al.* (2016), the dairy beef system includes the dairy cow, producing milk and the associated meat from slaughtered surplus calves and culled cow. It also includes the maintenance of the cow as a non-productive heifer. Table 1 shows the average, annual technical production and feed data required to determine EPCR and LUR for dairy beef livestock systems. These data were sourced from the National Farm Survey, an annual survey with representative samples of Ireland's agriculture sectors. The dominantly dairy breeds are Frisian and Jersey (DAFM, 2018*b*; O'Brien *et al.*, 2018; Donnellan *et al.*, 2020). Data about the rearing and fattening of dairy beef originated from Ashfield *et al.* (2014). Data about the mortality and live export of calves were sourced from the Department of Agriculture's animal identification and movement database (DAFM, 2018*b*). The replacement rate of the dairy herd was based on O'Brien *et al.* (2018). The dairy beef system produces 436 kg of milk solids from approximately 5500 litres/year; and after replacement and premature calf mortality produces 0.6 of a dairy beef calf annually.

Suckler beef production is similar to dairy, being a pasture-based system with spring calving. In contrast to dairy production, where milk is the main product, the primary production of suckler beef production is the beef animal, that is reared and fattened over the 26 month period from birth to slaughter (Foley *et al.*, 2011). The required production data were sourced from a National Farm Survey of the suckler beef sector, and therefore reflects the average suckler beef system. Dominant breeds were Aberdeen Angus; Limousine, Hereford and Charolaise (DAFM, 2018*b*; Donnellan *et al.*, 2020). This study includes the calf fattened to slaughter, the maintenance of its dam while she is suckling the calf and a share of the dam as a non-productive heifer divided across the calves of her lifetime. Table 1 outlines the average, annual diet consumed by the suckler beef system, based on life cycle inventory data from Foley *et al.* (2011). The suckler beef cow system has a herd cull rate of 18% and annually produces 0.85 beef calf per suckler cow before replacement and mortality (Maher *et al.*, 2008).

Unlike the two ruminant systems examined, pig production in Ireland is non-seasonal and predominantly reliant on imported human-edible feed (McAuliffe *et al.*, 2016). Similar to the suckler beef system, the pig system's primary product is the meat from the fattened pig. The extent of the pig system is the single pig, the maintenance of its sow across her litters that year, and includes the sow's carcase and the period as non-performing gilt divided across the piglets she produces in her lifetime (Manzanilla *et al.*, 2018). Table 1 outlines the average, annual diet consumed by the pig system (Edgar Garcia Manzanilla, personal communications, 2019). Pig meat and reproduction data were sourced from the 2018 National Herd Performance Report (Manzanilla *et al.*, 2018). The sow is culled after 2 years of production, producing 26.25 live piglets annually.

Calculating EPCRs

For each livestock system, we determined the refined EPCR, as given in Eqn (1) (Wilkinson, 2011; Laisse *et al.*, 2019; Mosnier *et al.*, 2021):

$$\text{EPCR} = \frac{\sum_{i=1}^{n} \text{HDP}_i \text{ used as feed}}{\text{HDP of 1 kg ASF}} \tag{1}$$

where HDP_i is the amount of human-digestible protein corrected for quality in feed ingredient i used in the livestock system ($i = 1, n$). The HDP value of each feed ingredient was corrected for

Table 1. Protein produced and feed consumed (kg dry matter) by the livestock systems under study

Livestock protein produced	Dairy beef	Suckler beef	Pig
Crude protein	258.84	95.65	17.87
PDCAAS[a] edible protein	254.18	88.00	17.52
DIAAS[b] edible protein	297.15	106.17	20.36
Feed used	**Dairy beef**	**Suckler beef**	**Pig**
Total grass	**7180.57**	**8182.46**	**10.45**
Pasture Grass	5129.52	5557.89	7.29
Grass Silage	2051.05	2831.25	3.16
Total concentrates	**1680.17**	**617.54**	**304.27**
Maize silage	86.40	0	0.21
Beet pulp,	316.51	0	0.75
Maize bran	356.24	129.68	79.08
Barley	498.44	179.09	42.22
Soya oil cakes and residues	172.46	74.11	58.69
Soya hulls	54.04	0	19.25
Molasses	26.84	30.88	0.02
Whey	0.72	0	0
Minerals	26.21	0	0.06
Sunflower oils	0.81	0	0
Wheat	83.25	55.58	104.06
Oil seed rape	84.95	92.63	0.11
Oats	59.66	55.58	0.03
Total feed	**8947.14**	**8800**	**314.92**

[a]Protein digestibility-corrected amino acid score.
[b]Digestible indispensable amino acid score.

Table 2. Crude protein values, HEP and protein digestibility scores (DIAAS[1] and PDCAAS[2]) of plant and animal products

Product	Crude protein (g/kg)	Estimated HEP (%)	DIAAS (%)	PDCAAS (%)
Barley	124.80[a]	61[d]	47.20[i]	61.00[k]
Maize	32.70[a]	15[d]	42.40[i]	47.30[i]
Broad bean	261.20[a]	95[d]	57.00i	54.10[n]
Potato	25.70[a]	90[e]	47.20[j]	80.00[o]
Rice (dry)	71.30[a]	80[f]	79.00[m]	81.00[k]
Sweet potato	15.40[a]	80[g]	3	76.00[m]
Soybean	364.90[a]	61[d]	99.60[i]	98.00[p]
Wheat	126.10[a]	66[d]	40.20[i]	51.00[q]
Oats	131.50[a]	80[f]	56.70[i]	67.00[r]
Oil seed rape	220.00[b]	59[i]	70.20[i]	86.00[s]
Milk	34.80[c]	100[d]	115.90[i]	100.00[o]
Pork	139.10[a]	75[h]	113.90[i]	98.00[t]
Beef	174.80[a]	63[h]	111.00[j]	92.00[o]

[1]Digestible indispensable amino acid score.
[2]Protein digestibility-corrected amino acid score.
[3]Animal product includes human edible fractions of meat and carcase offal.
[a](USDA, 2019), [b](Balalic et al., 2017), [c](FAO, 2013), [d](Laisse et al., 2019), [e](Camire et al., 2009), [f](Wilkinson, 2011), [g](CAST, 1999) [h](Ockerman and Hansen 1988) [i](Ertl et al., 2016), [j](Wolfe et al., 2018) [k](Nitrayová et al., 2018) [l](Hodgkinson et al., 2018), [m](Ertl et al., 2016), [n](Nosworthy et al., 2018), [o](van Zanten et al., 2016), [p](Phillips, 2016), [q](Schaafsma, 2005), [r](Rutherfurd et al., 2015), [s](Poisson et al., 2019) and [t](FDA, 1993).

protein quality by multiplying the crude protein value of each product with a digestible indispensable amino acid score (DIAAS; see Table 2). The DIAAS score of a feed/food ingredient reflects the lowest score of the true illeal digestibility of 11 indispensable amino acids that are present in feed or food items (Rutherfurd et al., 2015). Hence, the nominator is the sum of HDP in all feeds used in a livestock system, whereas the denominator is the sum of all HDP provided in the animal-sourced food (ASF). A ratio above 1 implies that animals eat more HDP than that they produce. A ratio below 1 does not automatically imply a net HDP contribution, as the EPCR does not include the fact that human-inedible biomass (e.g. grass or maize silage) can be produced on land suitable for human crop cultivation.

Calculating the LUR

The LUR as given in Eqn (2) compares the potential HDP from crops grown on land used to produce the livestock feed against the HDP in the livestock produce (van Zanten et al., 2016). To calculate the LUR, the methodology used by van Zanten et al. (2016) was adopted to also include protein quality:

$$\text{LUR} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} (\text{LO}_{ij} \times \text{HDP}_j)}{\text{HDP of 1 kg ASF}} \quad (2)$$

where LO_{ij} is the land area occupied for a year (in m^2), to cultivate the amount of feed ingredient i ($i = 1, n$) in the countries of origin j ($j = 1, m$) that are needed to produce 1 kg of HDP ASF; HDP_j is the maximum amount for human-edible protein corrected for protein quality (using DIAAS) that could by produced per year on area j. We enhanced the LUR of van Zanten et al. (2016) by determining this HDP for sustainable crop rotations instead of single crops (see later). The numerator of this ratio is the amount of HDP that potentially could be produced from the land area used to produce all feed for the animal, whereas the denominator contains the amount of HDP of 1 kg ASF similar to EPCR, therefore, the LUR is a single value. A ratio <1.0 demonstrates that livestock produce more HDP than crops, and could have a positive role in future HDP supply. We calculated the LUR for our three livestock systems in four steps, see below.

Quantifying land area for livestock feed

To quantify the area of agricultural land used for feed crops; we first needed to determine the country of origin of all feed ingredients. Feed import data from the Central Statistics Office of Ireland (CSO) provide the quantity and country of origin of the animal feed imported and outlines the quantity of feed grown (CSO, 2019). Second, we used the Global Agro-Ecological Zones (GAEZ) tool to verify the country of origin for each feed ingredient (FAO and IIASA, 2019). If GAEZ showed that a country is unsuitable to grow that specific feed ingredient, we redistributed the feed origin proportionally among the other countries that also cultivate that feed. Third, we used yield data from the FAO's corporate statistical database (FAOSTAT) to quantify the land area associated with the feed used in each country by a livestock system (FAO, 2019). As a single-feed ingredient is rarely the sole

driver of land-use, economic allocation was used to allocate the area of the crop land (e.g. oil seed rape) used among its different outputs (e.g. rapeseed meal used as feed and oil used as food). We used the Wageningen tool FeedPrint for its economic allocation function (Vellinga and Blonk, 2019).

To calculate the area of pasture used, we used information provided by Teagasc's Pasturebase Ireland tool, which is used to record grass growth at a paddock level (Hanrahan et al., 2017). This tool provides pasture production data from across Ireland, sourced from self-reported pasture productivity by farmers (Bogue, 2019). This allowed us to calculate a weighed value of average grass utilization rate of 8.4 tonnes of dry matter grass per hectare of pasture, which corresponds to previous studies (Hanrahan et al., 2018).

Determining suitability of land for human food crop cultivation

To calculate the area of pasture suitable for arable crops, we used an assessment of the soils of Ireland conducted by An Foras Talúntais in 1980 (Gardiner et al., 1980). This study outlined the proportion of all agricultural land suitable for crop production. Data from the CSO's Census of Agriculture provided the current area of arable crop and pasture. The land area currently under crop was subtracted from the total agriculture land, providing the area currently under pasture that is suitable for arable cropping (DAFM, 2016).

We assumed that all land that was used to cultivate feed crops was also suitable for food crops. The suitability of land associated with feed originating from Ireland was estimated for barley, oats, wheat, broad bean and oil seed rape, as these crops are commonly grown in Ireland (Askari and Holden, 2015). The suitability of the land associated with imported feed was estimated for eight common global food crops i.e. barley, oats, sweet potato, sorghum, maize, potato, wheat and rice, and three protein crops (high-protein yield), i.e. broad bean, oil seed rape and soybean (van Zanten et al., 2016; DAFM, 2018a). The GAEZ tool was used to verify whether the potential crops are capable to grow in the country studied (FAO and IIASA, 2019).

Calculating human digestible production from land suitable for crop production

We adapted the approach of van Zanten et al. (2016) to estimate the HDP from suitable land in Ireland, i.e. grassland and arable land. Unlike van Zanten, who determined HPD for single crops, we determined HDP for specific crop rotations to ensure soil quality over time. Using a previous study of sustainable soil management and crop rotations, we defined five feasible sustainable crop rotations for Ireland, see Table 3 (Askari and Holden, 2015). We then choose the crop rotation with the highest HDP.

To estimate the HDP from suitable land suitable outside Ireland, we first determined HDP yields of all eight global crops and three protein crops, and then averaged the HDP of the highest scoring global crop and the highest scoring protein crop.

To calculate HDP for each crop, we first derived the crop yield from the area of land used using yield data from FAOSTAT and the CSO yields (CSO, 2019; FAO, 2019). Subsequently, we multiplied the crop by its human edible portion (HEP) value to find the quantity suitable as food (Camire et al., 2009; Wilkinson 2011; Laisse et al., 2019). We then multiplied the yield by the crude protein content of each crop using values from the United States Department of Agriculture's (USDA) Food Data Central Nutritional Database (USDA, 2019). Finally, we calculated the

HDP available from the crop yield by multiplying it by a DIAAS score outlined in Table 2 (Consultation, 2011).

Calculating the human digestible production from the livestock

The amount of HDP in ASF was computed by multiplying the amount of livestock products by its HEP, which includes the offal from the carcase in Table 2. Then the crude protein values of the livestock products derived from the USDA Food Data Central Nutritional Database, by their DIAAS value in Table 2 (USDA, 2019).

Sensitivity analysis

Effect of protein quality

Besides DIAAS, the protein digestibility-corrected amino acid score (PDCAAS) is also often used to account for protein quality in food products. Before 2013, the FAO recommended to use the PDCAAS system. In 2013, the FAO changed its endorsement to the DIAAS system as it is considered more representative of true digestibility (FAO, 2013). It assesses true ileal amino acid digestibility of each indispensable amino acid, compared to the PDCAAS which only corrects for true faecal nitrogen digestibility (Rutherfurd et al., 2015). The PDCAAS methodology has been shown to disproportionally overestimate the digestibility of crop-sourced protein compared to animal-sourced protein (Ertl et al., 2016). To demonstrate the effect of the choice of protein quality scoring system used, we also computed our results using PDCAAS instead of DIAAS scores. The PDCAAS scores used for both crop and livestock products are outlined in Table 2.

Effect of pasture suitability for arable cropping

In the baseline situation, we assumed that the pasture suitability for arable crop production was 31%, using data on land-use suitability and current crop area (Gardiner et al., 1980; DAFM, 2011). This assumption affects the level of feed–food competition in ruminant systems. To determine the impact of this assumption on our results, we also calculated the LUR of the livestock production from pasture 100% suitable for arable crops against land completely unsuitable for arable crops (0%), with intervals of 10%.

Effect of crop rotations

In the baseline situation, we estimated HDP from land suitable for crop production using an average of the five different crop rotations (Askari and Holden, 2015). To determine the impact of this assumption on LUR, we also computed HDP using the individual rotations. These rotations and their LUR values are outlined in Table 3 which allows for the comparison of differing crop rotations' LUR value.

Results

Edible protein conversion ratio

Table 4 outlines the EPCR values of the three livestock systems examined. Both ruminant systems have by a lower than 1 EPCR value and thus create more HDP than they consume. Dairy beef's EPCR of 0.22 implies that 0.22 kg of crop-sourced HDP is consumed to produce 1 kg of animal-sourced HDP. Similarly, the EPCR of the suckler beef system is 0.29, which demonstrates that a suckler beef system consumes 0.29 kg of crop-sourced HDP to produce 1 kg of animal-sourced HDP. In contrast to the two feed-use efficient ruminant systems, the EPCR for the

Table 3. LUR crop rotations

Rotation	Dairy beef (DIAAS[a])	Dairy beef (PDCAAS)	Suckler beef (DIAAS[a])	Suckler beef (PDCAAS)	Pig (DIAAS[a])	Pig (PDCAAS)
Wheat, broad-bean	0.66	0.83	1.56	2.39	1.80	2.23
Wheat, potato	0.47	0.74	1.02	2.12	1.64	2.15
Wheat, broad-bean, oil seed rape	0.54	0.69	1.23	1.86	1.70	2.12
Wheat, broad-bean, barley	0.61	0.81	1.43	2.19	1.76	2.21
Wheat, broad-bean, barley, oat	0.63	0.81	1.48	2.33	1.77	2.24
Average crop rotation	**0.58**	**0.78**	**1.34**	**2.16**	**1.73**	**2.19**

[a]DIAAS is preferred baseline study.

Table 4. EPCR and LUR of Ireland's three livestock systems, based on two protein digestibility scores (DIAAS and PDCAAS)

System	EPCR HDP (DIAAS)	EPCR HDP (PDCAAS)	LUR HDP (DIAAS)	LUR HDP (PDCAAS)
Dairy beef	0.22	0.34	0.58	0.78
Suckler beef	0.29	0.40	1.34	2.16
Pig	1.51	1.90	1.73	2.19

monogastric pig system is greater than 1. It's EPCR value of 1.51 shows that 1.51 kg of crop-sourced HDP is needed to produce 1 kg of animal-sourced HDP.

Land use ratio

Table 3 demonstrates the LUR of three livestock systems; it includes each sustainable rotation for each livestock system and an average of the five sustainable crop rotations on the land used.

The average LUR of the dairy beef system is 0.58. This demonstrates that the land required to produce 1 kg of HDP from dairy beef production (milk and associated meat) could yield directly 0.58 kg of HDP from sustainable crop rotations. Unlike for dairy beef, the LUR for the suckler beef and pig system are larger than 1 (i.e. 1.34 for beef; 1.73 for pigs), implying that the land required to produce 1 kg of HDP from suckler beef or pigs could yield directly more HDP from sustainable crop rotations.

Sensitivity analysis

Effect of protein quality

As observed in Table 4, EPCR values based on DIAAS are lower than EPCR values on PDCAAS scores, implying that they value HDP from animal-source food relatively better. Similarly, LUR values based on DIAAS value livestock systems as more land efficient than LUR values based on PDCAAS (see Table 2). For example, the LUR in the dairy beef system scores changes from 0.78 in the PDCAAS score to 0.58 using the DIAAS methodology. Compared to the PDCAAS column, the DIAAS column has a higher digestibility value for animal protein and has lower values for the digestibility of plant protein (Table 2).

Effect of pasture suitability for arable cropping

Table 5 demonstrates that when the pasture of the ruminant system grazes is 0% suitable for arable crop production, dairy beef and

suckler beef systems' LUR are 0.25 and 0.28, respectively. When both ruminant systems are confined to marginal pasture then they are land-use efficient, the remaining feed–food competition comes from the arable land used for feed. In contrast in Table 5 where the ruminant systems are sourcing their grass from land that is 100% suitable for arable crop production, the LUR value of dairy beef becomes 1.35 and of suckler beef systems 3.77. Therefore, if the current ruminant systems are sourcing their grass from pasture that is 100% suitable for arable crop production, both livestock systems are land-use inefficient and are net losses to the supply of HDP.

In the baseline study as observed in Table 4, we observe that with 31% of pasture suitable for crop production, the dairy beef system is land-use efficient. It takes an increase in pasture suitability to 68% before the dairy beef system's LUR rises to 1. In regards to the suckler beef system, arable pasture needs to decrease to 21% before an LUR below 1 is achieved. The only change in the pig system comes from the piglet feeds which contain dairy products (e.g. whey); the rest of its feed already originates from arable crop production and its land is already fully engaged in feed–food competition with humans. Being a monogastric system reliant on human edible product for food, no change in pasture suitability will change the pig production system to an LUR of 1.

Effect of crop rotations

When we consider an LUR based on one crop rotation instead of the collective average (see Table 3), it is clear that the highest HDP yielding crop rotation is the wheat and broad-bean crop rotation. The LUR for the dairy beef, suckler beef and pig systems is 0.66, 1.56 and 1.80, respectively. The lowest HDP yielding crop rotation is the wheat and potato crop rotation. The LUR for the dairy beef, suckler beef and pig systems is 0.47, 1.02 and 1.64, respectively.

Discussion

This study aimed to determine the net contribution of three Irish livestock systems to the human edible protein supply, by quantifying enhanced EPCRs and LURs. We, therefore, first discuss the potential of the enhanced metrics to determine the net contribution of livestock systems to human protein supply and subsequently evaluate results and their implications for the development of future-food systems.

Potential of enhanced metrics

Our EPCR results indicate that ruminant systems reliant on pasture, especially dairy systems, are more feed-use efficient and positive HDP producers compared to the monogastric

Table 5. LUR pasture suitability (based on DIAAS[a])

Percentage suitable	Dairy beef	Suckler beef	Pig
0	0.25	0.28	1.72
10	0.36	0.62	1.72
20	0.47	0.97	1.73
30	0.58	1.32	1.73
40	0.69	1.67	1.74
50	0.80	2.02	1.74
60	0.91	2.37	1.75
70	1.02	2.72	1.75
80	1.13	3.07	1.75
90	1.24	3.42	1.76
100	1.35	3.77	1.76

[a]DIAAS is preferred baseline study.

concentrate fed pig system. These results confirm the finding of others, such as Wilkinson (2011), van Zanten *et al.* (2016), Laisse *et al.* (2018), Laisse *et al.* (2019) and Mosnier *et al.* (2021). They also demonstrated that cattle fed with inedible fodder are efficient producers of ASF (Wilkinson, 2011; van Zanten *et al.*, 2016; Laisse *et al.*, 2018; Mosnier *et al.*, 2021). Wilkinson. (2011) Laisse *et al.* (2019) and Mosnier *et al.* (2021), for example, compared pasture-based cattle systems with concentrate-based cattle systems and concluded that unlike pasture-based cattle, concentrate-based cattle are inefficient protein producers. Their results on monogastric pigs also correspond to ours whereby, pig systems fed with HDP intense grains are demonstrated to be inefficient HDP producers (Wilkinson, 2011). Consequently, we can observe that the EPCR methodology endorses feeding livestock with human inedible products and therefore favours the position of placing cattle on fodder as an efficient use of land.

The methodology of the EPCR, however, fails to account for the potential of the land used to produce food crops for humans directly. In other words, it does not account for the potential alternative land-use in which the feed and fodder crops used, replaces human edible crops. Consequently, the EPCR cannot accurately reflect whether livestock production systems are potentially net producers of food (van Zanten *et al.*, 2016).

Our results from the LUR show that using the EPCR metric to advise how to optimize food production may lead to incorrect recommendations for land-use and land-use change. When we compare the EPCR of the three livestock systems in Table 4 with their LUR values, we observe substantial differences in the livestock systems efficiency values and their efficiency rankings. According to the LUR, the dairy beef and suckler beef systems are significantly less efficient than their EPCR values suggest. This is especially apparent with suckler beef being considered by the EPCR to be feed-use efficient, while considered to be land-use inefficient when applying the LUR. Our results confirm the findings of van Zanten *et al.* (2016) who demonstrated a dairy-beef system which is feed-use efficient, i.e. EPCR <1, but land-use inefficient, i.e. LUR >1 (van Zanten *et al.*, 2016). Hence, we cannot consider the EPCR alone to be a suitable metric for developing future-food systems.

The LUR appears the most inclusive metric to understand the net contribution of livestock systems to the human protein supply.

We enhanced the LUR by including protein quality and crop rotations. When considering which digestibility score should be used to include protein quality, the ramifications of the choice can have significant impacts. The DIAAS methodology more accurately outlines the dietary uptake of HDP as it calculates digestibility at the end of the small intestine which better reflects the true amount of amino acids absorbed. The PDCAAS instead represents the uptake of protein from a faecal sample which then includes all gut micro flora activities, which affects its accuracy (FAO, 2013). This is why the PDCAAS methodology considers crop-sourced protein to have a higher digestibility value than it may truly have. Consequently, comparing crop-sourced and animal-sourced HDP using PDCAAS would be inaccurate as it does not compare the true amount of amino acids absorbed (Ertl *et al.*, 2016). As observed in Table 2 the PDCAAS value for potatoes of 80% declines to 47% with DIAAS compared to milk which remains fully digestible. Our results demonstrate that the PDCAAS scores skew results to crop-sourced protein. Further to this, the inaccuracies altered the recommended alternative crops, providing incorrect land use recommendations. Hence, the DIAAS system is preferable as when we are meeting future dietary demands and the ability for future-food systems to meet demand, accurate metrics are needed to ensure demand can be met efficiently.

We, moreover, were the first to consider crop rotations in the LUR. Van Zanten *et al.* (2016) used a single crop, either wheat or potatoes (see Table 6) which are not usually included in the human diet for their protein content but are common crops cultivated in the Netherlands (FAO and IIASA, 2019). However, mono-cropping can lead to soil exhaustion and may reduce soil productivity (Askari and Holden, 2015). Our results showed that accounting for crop rotations reduced the LUR value of about 30% in the dairy beef system compared to the single highest HDP yielding crop as done in earlier LUR studies. Crop rotations are not only relevant to maintain soil quality, but to also provide a diverse set of food to fulfil nutrition requirements (Willett *et al.*, 2019). Hence, we argue that the use of a crop rotation that does not exhaust the soil but includes protein intensive crops with the aim to deliberately replace the livestock HDP is an important innovation of the LUR.

Implications for future-food systems

It is clear in our baseline study of Ireland that as it exists currently the dairy beef system is land-use efficient unlike its suckler beef counterpart. The results show that when the ruminant systems are on marginal pasture wholly unsuitable for arable crops; the feed–food competition between crops and livestock only occurs on the land used for cultivating livestock's concentrate feed (see Table 5). In that scenario, the dairy beef and suckler beef system's LUR values are 0.25 and 0.28, respectively. In the scenario where pasture is wholly suitable for arable crop production it is clear that the ruminant system's LUR changes from being land-use efficient to being land-use inefficient. This demonstrates that both ruminant systems when sourcing its pasture from marginal land are net producers of HDP, although the dairy beef system is a more efficient use of pasture.

It could be argued that the role for livestock in Ireland's future-food system is confining them to marginal land which in Ireland can be highly productive pasture due to the favourable soils and climate (Hanrahan *et al.*, 2017). This can minimize feed–food competition and maximize food production from Ireland's

Table 6. Alternative LUR calculated with differing methodologies

System	Country	LUR
Dairy beef[a]	Netherlands	0.67
Dairy beef[b]	Netherlands	2.10
Laying hen[c]	Netherlands	2.08
Laying hen[d]	Netherlands	1.70
Laying hen[e]	Netherlands	0.66
Laying hen[f]	Netherlands	0.30
Suckler beef[g]	North-East USA	52.90
Dairy beef[g]	North-East USA	3.40

[a](van Zanten et al., 2016) Dairy beef on peat soils replaced with potatoes, (van Zanten et al., 2016) dairy beef on arable spoils replaced with wheat, [c](van Zanten et al., 2016) laying hen system, [d](van Hal et al., 2019) laying hen with economic allocation, [e](van Hal et al., 2019) laying hens optimized to limit feed–food competition with economic allocation, [f](van Hal et al., 2019) laying hens with food-based allocation, [g](Tichenor et al., 2017) including protein crops mainly soybean as the alternative crop.

agricultural land. Furthermore, when considering the agriculture sector in Ireland from a feed–food competition perspective, the trend of land-use change from arable production to pasture increases the average LUR (CSO, 2020). One could even argue from a feed–food perspective that pasture on arable land should be converted to arable crops. If this arable land is instead used in the crop rotations used in this study; then more HDP could be produced with some potential for livestock feed from LCB. This could significantly increase the amount of HDP produced in Ireland. However, one should not forget that such a land-use change results in the GHG emissions and biodiversity loss and based on the most recent National Farm Survey Results would result in reduced farm profitability on average (Taube et al., 2014; Donnellan et al., 2020).

When considering Ireland's pig system that is land-use inefficient, it could be argued that if the pig system is reliant on LCB then the LUR values should decrease as the land area needed for feed production would decline. This has been studied in Zu Ermgassen et al. (2016) who has demonstrated that including food-waste in a pig's diet can reduce the area of arable land needed as feed by about one-fifth (Zu Ermgassen et al., 2016). Hence, opportunity exists to modify a monogastric system towards land-use efficiency.

This argument applies to our ruminant system's LUR; there is an option to limit its feed to marginal pasture and LCB which could increase its land-use efficiency. Van Zanten et al. (2016) calculated that if we feed livestock only with leftover streams and grass we could produce about a third of our daily dietary protein requirements (van Zanten et al., 2016). Considering that currently Ireland is a net exporter of ASF, limiting livestock production to LCB would mean a reduction of protein produced and exported.

Finally, Godfray (2015) argued that although livestock numbers need to be reduced globally, they should be increased where they are most efficient to maximize food production efficiency. Future-food demands cannot be met with land extensification but can be met from land-use optimization (Schader et al., 2015). The LUR could allow policy makers to choose which livestock system to use and where it should be placed on the future landscape. It could be used to calculate where it is most efficient to place livestock for the global future-food systems. However, as pointed out by Mosnier et al. (2021), land-efficient grass-based ruminant systems not only contribute to food supply, but can also deliver other ecosystem services, such as nutrient cycling, carbon sequestration or biodiversity conservation. Hence, if the LUR is utilized with other metrics that quantify nutrient flows and GHG emissions in a multi-criteria framework; then, it could be used as a more holistic tool for planning optimal future-food systems within planetary boundaries at regional, national and global levels.

Conclusion

The enhanced LUR appears the most inclusive metric as it addresses both feed-use and land-use efficiency. It, however, requires knowledge on the suitability of land for arable production, crop rotation and pasture yields, and protein evaluation scoring systems. The enhanced LUR appeared 0.58 for dairy beef, 1.34 for suckler beef and 1.73 for pig production in Ireland. Therefore, the dairy beef system is the most efficient livestock system examined and the only livestock system that is a net positive contributor to the global supply of HDP as it currently exists and on marginal land is still significantly more efficient than suckler beef production.

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References

Alexandratos N and Bruinsma J (2012) World agriculture towards 2030/2050: the 2012 revision. Available at https://doi.org/10.22004/ag.econ.288998.

Ashfield A, Wallace M, Prendiville R and Crosson P (2014) Bioeconomic modelling of male Holstein-Friesian dairy calf-to-beef production systems on Irish farms. *Irish Journal of Agricultural and Food Research* **53**, 133–147.

Askari MS and Holden NM (2015) Quantitative soil quality indexing of temperate arable management systems. *Soil and Tillage Research* **150**, 57–67.

Balalic I, Jeromela A, Crnobarac J, Terzić S, Radic V, Miklic V and Jovičić D 2017. Variability of oil and protein content in rapeseed cultivars affected by seeding date. *Emirates Journal of Food and Agriculture* **29**, 404–410.

Bía B (2019) Export Performance & Prospects 2018–2019. Available at https://doi.org/.

Bogue F (2019) *RE: Grass Production per County of Ireland* 2018. Type to Hennessy, D.

Bowles N, Alexander S and Hadjikakou M (2019) The livestock sector and planetary boundaries: a 'limits to growth' perspective with dietary implications. *Ecological Economics* **160**, 128–136.

Bradford E, Baldwin L, Blackburn H, Cassman K, Crosson P, Delgado E, Fadel J, Fitzhugh H, Gill M, Oltjen J and Vavra M and Wilson R (1999) Animal agriculture and global food supply (Vol. 135). Council for Agricultural Science.

Camire ME, Kubrow S and Donnely D (2009) Potatoes and human health. *Critical Reviews in Food Science and Nutrition* **49**, 823–840.

Campbell BM, Beare DJ, Bennett EM, Hall-Spencer JM, Ingram JSI, Jaramillo F, Ortiz R, Ramankutty N, Sayer JA and Shindell D (2017) Agriculture production as a major driver of the earth system exceeding planetary boundaries. *Ecology and Society* **22**, 8. https://doi.org/10.5751/ES-09595-220408.

Consultation FE (2011) Dietary protein quality evaluation in human nutrition. *FAO Food Nutrition Papers* **92**, 1–66.

CSO (2019) RE: Feed Data. Type to Hennessy, D.

CSO (2020) Historic land cover. In: Office, C. S. (ed.).

DAFM (2011) Census of Agriculture 2010.

DAFM (2016) Farm Structure Survey. In: Teagasc (ed.).

DAFM (2018*a*) Background Paper Cereals, Horticulture and Organics. In: Marine, D. O. A. F. A. T. (ed.).

DAFM (2018*b*) AIM Bovine Statistics Report. In: (DAFM), D. O. A. F. A. T. M. (ed.).

De Boer IJ and Van Ittersum MK (2018) *Circularity in Agricultural Production*. The Netherlands: Wageningen University & Research.

Donnellan T, Moran B, Lennon J and Dillon E (2020) Teagasc National Farm Survey 2019. In: Surveys, A. E. A. F. (ed.).

EPA (2018) Ireland's national inventory report: greenhouse gas emissions 1990–2016 reported to the united nations framework convention on climate change. 59-60. In Agency EP (ed.), Johnstown Castle, Co. Wexford, Ireland: Environmental Protection Agency.

Ertl P, Knaus W and Zollitsch W (2016) An approach to including protein quality when assessing the net contribution of livestock to human food supply. *Animal: An International Journal of Animal Bioscience* 10, 1883–1889.

FAO (2013) Dietary protein quality evaluation in human nutrition. Viale delle Terme di Caracalla, 00153 Rome, Italy: FAO.

FAO (2019) FAOSTAT Website [Online]. Available at http://www.fao.org/faostat/en/#home.

FDA (1993) Policy – food labeling: mandatory status of nutrition labeling and nutrient content revision, format for nutrition label. In Administration FAD (ed.), Food and Drug Administration: FDA.

Foley PA, Crosson P, Lovett DK, Boland TM, O'mara FP and Kenny DA (2011) Whole-farm systems modelling of greenhouse gas emissions from pastoral suckler beef cow production systems. *Agriculture, Ecosystems & Environment* 142, 222–230.

Gardiner MJ, Radford T and Foras T (1980) *Soil associations of Ireland and their land use potential: explanatory bulletin to the soil map of Ireland*, 1980, Dublin, Foras Talúntais. Available at https://www.teagasc.ie/media/website/environment/soil/General.pdf.

Gerber PJ, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A and Tempio G (2013) *Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities*, Food and Agriculture Organization of the United Nations (FAO). 925107920X. Available at http://www.fao.org/docrep/018/i3437e/i3437e00.htm.

Godfray HCJ (2015) The debate over sustainable intensification. *Food Security* 7, 199–208.

Hanrahan L, Geoghegan A, O'donovan M, Griffith V, Ruelle E, Wallace M and Shalloo L (2017) PastureBase Ireland: a grassland decision support system and national database. *Computers and Electronics in Agriculture* 136, 193–201.

Hanrahan L, Mchugh N, Hennessy T, Moran B, Kearney R, Wallace M and Shalloo L (2018) Factors associated with profitability in pasture-based systems of milk production. *Journal of Dairy Science* 101, 5474–5485.

Hodgkinson SM, Montoya CA, Scholten PT, Rutherfurd SM and Moughan PJ (2018) Cooking conditions affect the true ileal digestible amino acid content and digestible indispensable amino acid score (DIAAS) of bovine meat as determined in pigs. *Journal of Nutrition* 148, 1564–1569.

FAO and IIASA (2019) GAEZ Tool. Rome: FAO.

Laisse S, Baumont R, Veysset P, Benoit M, Madrange B and Peyraud J (2018) The net contribution of ruminant production to the protein supply for humans. *European Grassland Federation*. Cork, Ireland.

Laisse S, Baumont R, Dusart L, Gaudré D, Rouillé B, Benoit M, Remond D and Peyraud JL (2019) 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.

Maher P, Good M and More SJ (2008) Trends in cow numbers and culling rate in the Irish cattle population, 2003 to 2006. *Irish Veterinary Journal* 61, 455.

Manzanilla EG (2019) RE: Pig production and diet. Type to Hennessy, Donagh.

Manzanilla EG, Carrol C, Mccutcheon G, Mckeon M, Quinn A, Mccrum E, Clarke L, Lawlor P, Boyle L and O'driscoll K (2018) National Pig Herd Performance. In: Development, P. (ed.).

Mcauliffe GA, Chapman DV and Sage CL (2016) A thematic review of life cycle assessment (LCA) applied to pig production. *Environmental Impact Assessment Review* 56, 12–22.

Mosnier C, Jarousse A, Madrange P, Balouzat J, Guillier M, Prilo G, Mertens A, Oriordan E, Pahmeyer C and Hennart S (2021) Evaluation of the contribution of 16 European beef production systems to food security. *Agricultural Systems*, 190, https://doi.org/10.1016/j.agsy.2021.103088.

Mottet A, De Haan C, Falcucci A, Tempio G, Opio C and 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.

Naylor R, Steinfeld H, Falcon W, Galloway J, Smil V, Bradford E, Alder J and Mooney H (2005) Agriculture. Losing the links between livestock and land. *Science* 310, 1621–1622.

Nitrayová S, Brestenský M and Patráš P (2018) Comparison of two methods of protein quality evaluation in rice, rye and barley as food protein sources in human nutrition. *Potravinarstvo Slovak Journal of Food Sciences* 12, 762–766.

Nosworthy MG, Medina G, Franczyk AJ, Neufeld J, Appah P, Utioh A, Frohlich P and House JD (2018) Effect of Processing on the In Vitro and In Vivo Protein Quality of Beans (*Phaseolus vulgaris* and *Vicia faba*). Nutrients, 10. Available at https://doi.org/10.3390/nu10060671.

O'Brien D, Moran B and Shalloo L (2018) A national methodology to quantify the diet of grazing dairy cows. *Journal of Dairy Science* 101, 8595–8604.

Ockerman HW and Hansen CL (1988) *Animal by-product processing*. Weinheim: VCH, pp. 19. http://hdl.handle.net/1811/25205.

Phillips SM (2016) The impact of protein quality on the promotion of resistance exercise-induced changes in muscle mass. *Nutrition & Metabolism* 13, 64.

Poisson E, Trouverie J, Brunel-Muguet S, Akmouche Y, Pontet C, Pinochet X and Avice J-C (2019) Seed yield components and seed quality of oilseed rape are impacted by sulfur fertilization and its interactions with nitrogen fertilization. *Frontiers in Plant Science* 10, 1–14. https://doi.org/10.3389/fpls.2019.00458.

Poore J and Nemecek T (2018) Reducing food's environmental impacts through producers and consumers. *Science* 360, 987–992.

Ramankutty N, Mehrabi Z, Waha K, Jarvis L, Kremen C, Herrero M and Rieseberg LH (2018) Trends in global agricultural land use: implications for environmental health and food security. *Annual Review of Plant Biology* 69, 789–815.

Rutherfurd SM, Fanning AC, Miller BJ and Moughan PJ (2015) Protein digestibility-corrected amino acid scores and digestible indispensable amino acid scores differentially describe protein quality in growing male rats. *The Journal of Nutrition* 145, 372–379.

Schaafsma G (2005) The protein digestibility-corrected amino acid score (PDCAAS) – a concept for describing protein quality in foods and food ingredients: a critical review. *Journal of AOAC International* 88, 988–994.

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 and 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.

Taube F, Gierus M, Hermann A, Loges R and Schönbach P (2014) Grassland and globalization – challenges for north-west European grass and forage research. *Grass and Forage Science* 69, 2–16.

Tichenor NE, Van Zanten HHE, De Boer IJM, Peters CJ, Mccarthy AC and Griffin TS (2017) Land use efficiency of beef systems in the Northeastern USA from a food supply perspective. *Agricultural Systems* 156, 34–42.

USDA (2019) USDA Food Composition Databases. In: Agriculture, U. S. D. O. (ed.).

Van Hal O, Weijenberg AAA, De Boer IJM and Van Zanten HHE (2019) Accounting for feed–food competition in environmental impact assessment: towards a resource efficient food-system. *Journal of Cleaner Production* 240, 118241.

Van Zanten HHE, Mollenhorst H, Klootwijk CW, Van Middelaar CE and De Boer IJM (2016) Global food supply: land use efficiency of livestock systems. *The International Journal of Life Cycle Assessment* 21, 747–758.

Vellinga T and Blonk H (2019) Feedprint Tool. In: Wageningen (ed.). Wageningen.

Wilkinson JM (2011) Re-defining efficiency of feed use by livestock. *Animal: An International Journal of Animal Bioscience* 5, 1014–1022.

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, Declerck F, Wood A, Jonell M, Clark M, Gordon LJ, Fanzo J, Hawkes C, Zurayk R, Rivera JA, De vries W,

Majele Sibanda L, Afshin A, Chaudhary A, Herrero M, Agustina R, Branca F, Lartey A, Fan S, Crona B, Fox E, Bignet V, Troell M, Lindahl T, Singh S, Cornell SE, Srinath Reddy K, Narain S, Nishtar S and Murray CJL (2019) Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. *Lancet* **393**, 447–492.

Wolfe RR, Baum JI, Starck C and Moughan PI (2018) Factors contributing to the selection of dietary protein food sources. *Clinical Nutrition* **37**, 130–138.

Zu Ermgassen EKHJ, Phalan B, Green RE and Balmford A (2016) Reducing the land use of EU pork production: where there's swill, there's a way. *Food Policy* **58**, 35–48.