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Abstract

French dairy systems (cow, goat and ewe) have a wide variety of feeding systems. The feed consumed may compete with human food (cereals, grain legumes, silage maize) or not (grassland, rangeland). Gross and net energy and protein efficiencies were assessed. The net approach takes better account of feed-food-fuel competition. Dairy systems are net consumers of energy and net producers of protein for humans, with the best results from grassland systems. At a national scale, net protein efficiency is 1.16 for ewes, 1.12 for goats and 1.88 for cows. Edible energy feed consersion efficiencyis 0.63, 0.54 and 1.00 respectively. There is room for technical improvement in all three sectors, although the variability is sometimes considerable. In order to disseminate these results, innovation groups made up of members of the sectors and livestock farmers have made it possible to better target the methods of communicating the main results of the ERADAL project. In addition, a range of media was created and made available to everyone throughout the ERADAL project.

Key words: competition, efficiency, milk, meat

1. Introduction

Ruminants have the ability to convert resources that are not human-edible, such as grass, into high-quality animal products that can make a significant contribution to human nutrition and food security. Indeed, animal products play a major role in satisfying the growing demand for human food (Mottet et al., 2017). Despite this, animal production is facing growing challenges in terms of animal welfare, product quality and environmental impact (Steinfeld et al., 2006). Dairy production will therefore be socially acceptable in the future if it is profitable for farmers, environmentally virtuous, legitimate in terms of land use and maintenance, and competes little with human food. At the same time, these major objectives are confronted with the need to reduce the quantity of food consumed by humans in ruminant feed, and to reduce enteric methane emissions (Coppa et al., 2021).

Ruminants are considered inefficient in the conversion of feed (protein and energy) and can compete directly in the use of arable land for human food. Peyraud and Peeters (2016) calculated that it takes more than 3 kg of plant protein to produce 1 kg of protein via milk, and 5 to 10 kg to produce 1 kg of protein via beef. However, these figures do not distinguish between food consumed by animals and human-edible, and food that is not (e.g. grass or by-products of the agri-food and biofuel industries). The

CAST report (1999) was the first to propose an approach for characterising the edible part of animal feed. More recently, Wilkinson (2011) has provided results using this approach for specific systems. On a global scale, Mottet et al (2017) estimated that 86% of livestock feed consumption, in terms of dry matter, was made up of raw materials that are not currently human-edible. What's more, compared with plant foods, animal products offer major advantages in human nutrition, with good protein digestibility and a wealth of vitamins, macro- and micro-elements.

To better understand the contribution of livestock farming to human food production, we need to calculate efficiency ratios. The ratio between the quantity of protein and energy produced by animal products and consumed by humans (milk and meat), and the quantity of plant protein and energy consumed by animals but potentially human-edible, is extremely relevant; this is known as net efficiency. This approach seems more relevant and informative for tackling feed-food competition than one based solely on the total quantity of energy or protein used to produce 1 kg of animal protein (Wilkinson, 2011; Ertl et al., 2016). Wilkinson (2011) proposed a redefinition of the efficiency of feed use by farm animals, and was thus the first to distinguish between human-edible and non-human-edible fractions in animal feed. His work aimed to characterise 'feed-food' competition using both gross and net feed conversion efficiencies for ruminant, pig and poultry systems. Ertl et al (2016) and Laisse et al (2018) used the same approach to estimate gross and net protein and energy efficiencies for different animal systems. The conclusions of these publications were similar: ruminants do not compete with humans for food resources. They have the potential to transform roughage and non-human-edible resources into animal products of high nutritional quality. But overall, results of this kind are still lacking, particularly for small dairy ruminants.

The studies that have been carried out to date therefore clearly indicate that it is essential to take better account of the fraction of feed that is not consumed by humans, in terms of both energy and protein, if we are to fully understand the nature of the 'feed-food' competition, particularly in the case of dairy ruminants. The aim of the CASDAR ERADAL project was therefore to determine gross and net energy and protein efficiencies for the main dairy sectors in France (ewes, goats and cows). To do this, we analysed a large and detailed database reflecting the wide diversity of dairy systems. The results have been used to produce a range of materials for farmers, advisors, learners and teachers.

2. Materials and methods

2.1 A methodology shared by the animal technical institutes

The methodology for calculating the conversion efficiency of plant feed consumed by animals into animal products intended for human consumption was defined as part of the work of the GIS Elevages Demain back in 2015 (https://www.gis-elevages-demain.org/). It is shared by the ruminant, pig and poultry sectors at national level. It consists of calculating the ratio between a farm's animal products and the food consumption of plant products by animals from the same farm. Two criteria are assessed: protein and energy. For each criterion, two levels of efficiency are considered: i) feed conversion efficiency is the ratio between all animal products (milk and meat) consumed by humans and all consumption of plant products (fodder and concentrates), and ii) edible feed conversion efficiency is the same ratio but considering only the fraction of animal feed consumed by humans. Edible efficiency seems better suited to assessing feed/food competition. By semantic choice, the term "human-edible" always refers to human food. Example of the calculation formula for protein:

- protein feed conversion efficiency (pFCE) = kg of human-edible animal protein produced on the farm / kg of plant protein consumed by the animals

- Edible protein feed conversion efficiency (eeFCE) = kg of human-edible animal protein produced on the farm / kg of human-edible plant protein consumed by the animals.

To make these calculations, it is essential to characterise the energy and protein fractions that can be consumed by humans for the feed consumed by dairy ruminants (Laisse et al., 2016). For example, the human-edible protein fraction of wheat is 66% (Figure 1).

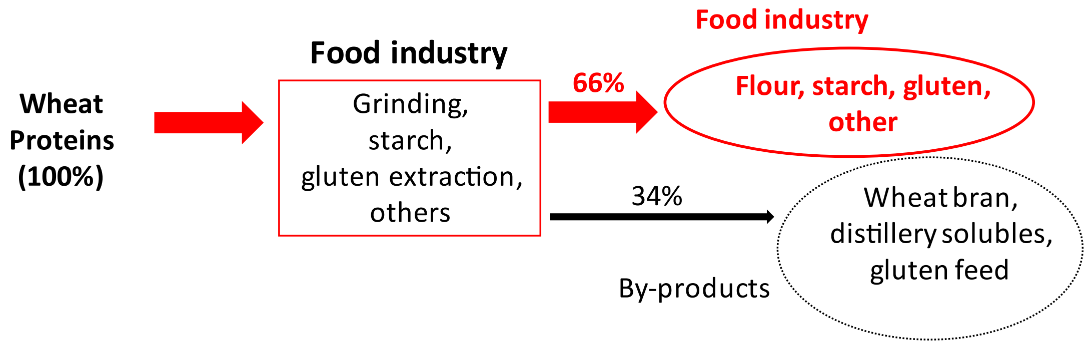

Diagram 1 Proportion of human-edible and non-human-edible proteins, using wheat as an example

This means that processing wheat for human consumption currently uses an average of 66% of wheat protein. In contrast, the protein fraction will be 0% for rapeseed and sunflower oilcake (table 1). For fodder, the protein fraction is 0%, except for maize silage (10%) because of its grain content, which could potentially be used for human consumption. The same work was done on animal products (milk and meat). All the milk produced and sold by dairy farms can be consumed by humans. For meat, the human-edible fraction of dairy animals was made up of meat, offal and by-products currently consumed in France. These figures vary from one dairy species to another due to differences between the types of animal (adult/young, male/female), the initial protein and energy content of the meat, the carcass yield and the edible fraction of the different products.

		Proportion of energy consumed by humans (%)	Proportion of protein consumed by humans (%)
Forages	Pastured or grazed grass	0	0
	Corn silage	32	10
	Hay, haylage and grass silage	0	0
	Immature cereal silage	70	70
Concentrates	Faba bean	83	92
	Wheat	68	66
	Soya meal	38	60
	Rapeseed meal	0	0
	Commercial feed 40% MAT (Total Nitrogen Matter)	24	32
	Beet pulp	0	0
Milk	Sheep's milk	100	100
	Goat's milk	100	100
	Cow's milk	100	100
Meat	Lamb meat	39	45
	Kid meat	48	63
	Dairy cow meat	31	55

Table 1 Proportions of energy and protein consumed by humans in certain dairy ruminant feeds and some animal products.

2.2 Resources mobilised

2.2.1 The DIAPASON database

The Diapason database (Inosys-Réseaux d'élevage, Idele, Chambres d'agriculture) was used to determine feed resource use efficiency. The data used are 'farm-years' and range from 2012 to 2016 for the three sectors. 1382 data from 498 dairy cow farms, 847 data from 274 dairy goat farms and 343 data from 108 dairy sheep farms were retained for the efficiency calculations. These farms specialise in dairy production. This database contains the main information on the farms (Charroin et al., 2005). The results are available to the public for advice and decision-making within farms and sectors. The database is structured and organised according to means of production, overall farm structure, zootechnical performance, animal production levels and economic results.

For dairy cows, the data was classified into five groups: lowland farms with >30% maize in the forage area (C-L30+), lowland farms with 10–30% maize in the forage area (C-L1030), lowland farms with <10% maize in the forage area (C-L10-), mountain farms with >10% maize in the forage area (C-M10+), and mountain farms with <10% maize in the forage area (C-M10-).. These groups give a good representation of the diversity of dairy cow systems in France, according to location (plains and mountains), and according to the proportion of maize silage in the ration.

The data from the dairy sheep systems were also divided into five groups, according to feeding strategy and location: selling milk without processing in Corsica (S-DC), no transhumance in Pyr´en´ees-

Atlantiques (S-NPA), transhumance in Pyr´en´ees-Atlantiques (S-TPA), natural grasslands in Roquefort area (S-GR), and mountains in Roquefort area (S-MR). Transhumance refers to the periodic migration of sheep from the plains to the mountains for the summer period. These regions, all located in the south of France, are the main producers of ewe's milk.

The dairy goat systems were separated into nine groups, according to the main forage used: cut-and-carry (G-CC), baled grass (G-BG), maize silage (G-MS), mixed legume-grass hay (G-MH), legume hay (G-LH), extensive grass production and in-barn feeding G-EB), low-inputs and pasture (G-EP), mainly pasture (G-PM), and dry diet (G-DD).

It is important to note that while the INOSYS database contains diverse and detailed information on goat, sheep and beef dairy systems, reflecting the wide diversity of French dairy systems, it does not accurately represent the proportions of each system across the country as a whole. A relative weighting, using official data, was carried out in order to better estimate the share of each group at national level. For goats (Bossi and Jost, 2016) and dairy sheep, this weighting was carried out using the results of the RA 2010. For dairy cattle, the Observatoire de l'alimentation des vaches laitières was used for this weighting (Idele and Cniel, 2015).

2.2.2 Experimental farms

Experimental farms and agricultural college farms were used to study their efficiency results, test practices and their impact on efficiency, and suggest ways of improving the situation for producers (Table 2).

	La Blanche Maison (50)	Trévarez (29)	Inra Ferlus (86)	EPL Saint-Lô Thère (50)	EPL Olivier de Serres Aubenas (07)	EPL La Cazotte Saint-Affrique (12)
Soil and climate context	Plaine Watered and temperate zone	Plaine Cool, wet zone	Plaine Drying zone	Plaine Watered and temperate zone	Plaine Mediterranean zone	Plaine Drying zone
Dairy systems	Multi-crop livestock farming Meadows Agroecology	Making the most of grass Mobile robot and grazing Agrobiology	Food self-sufficiency Pasture and/or ventilated hay Agroecology	Meadows Agroecology Technology hall	Making the most of grass Grazing Farm processing	Power supply Protein self-sufficiency Production Roquefort AOC
Number of animals	90	55	180	45	120	600
Species	Cow	Cow	Goat	Cow	Goat	Ewes
Breeds	Normande	3-way crossing in Hostein x Normande x Jersiaise	Alpine	Holstein	Alpine	Lacaune

Table 2 Description of the experimental dairy systems studied in the project

2.2.3 Innovation groups

Innovation groups were set up with the aim of creating a dynamic with as many willing players as possible from the dairy sectors involved. The aim was to exchange ideas, put forward arguments and propose indicators and technical solutions to improve the efficient use of feed resources in beef, sheep and goat dairy production. To achieve this, four innovation groups were set up in areas where experimental systems and agricultural colleges were being monitored: two groups focusing on dairy cattle in Brittany and Normandy; a dairy goat group in the Western Basin; and a dairy sheep group in Aveyron. These groups were made up of project members, volunteer farmers who were efficient and committed to improving their practices in order to achieve greater efficiency, and learners.

3. Results

3.1 Dairy ruminants' rations are mainly made up of feedstuffs that cannot be consumed by humans

Having defined the proportions of energy and protein in feed consumed by animals that can be consumed by humans (examples in Table 1), it is now possible to characterise the percentage of these two fractions that cannot be consumed by humans (Table 3 and Table 4). Thus, in what is consumed by ruminants:

- In dairy cattle (C), 86% of the energy and 89% of the protein are not human-edible (Rouillé et al., 2020);
- In dairy goats (G), 83% of the energy and 86% of the protein are not human-edible (Jost et al., 2019);
- in dairy sheep (S), 88% of the energy and 89% of the protein are not human-edible (Jost et al., 2019).

Dairy ruminants therefore use a majority of feedstuffs that cannot be used for human consumption and, from this, produce animal products with a high nutritional value. There is little competition in the use of resources between ruminant feed and human food for energy and protein.

3.2 Dairy systems that are net energy consumers and net protein producers

Dairy cattle, goat and sheep systems show low levels of energy feed consersion efficiencyenergy feed consersion efficiency with little variability: 0.14 in C, 0.09 in G and 0.07 in S (Table 3). This means, for example, that for every 1 kcal of plant energy consumed by a flock of dairy ewes, only 0.07 kcal is available for human consumption via milk and meat products. However, although it remains less than 1, this efficiency improves when the fraction consumed by the flock that cannot be consumed by humans is taken into account. Dairy systems have net energy efficiencies of 0.54 in G and 0.63 in S (Table 3). Only the C systems reach equilibrium at 1.00: they therefore consume as many human-edible kcal as they produce. Edible energy feed consersion efficiency shows low inter-system variability in S and high in C. There is little variation between farms of the same species. It varies from 0.67 to 2.67 in C, from 0.39 to 0.73 in G and from 0.59 to 0.67 in S. On the other hand, intra-system variability is greater. Within a sector, when we consider farms with comparable systems (5 systems in C, 5 in S and 9 in G), the variation in net efficiency criteria is very significant between farms, even within each type of system. This variation between farms in the same system is much greater than the variation between the systems studied. However, this opens the way to technical solutions for improving this criterion, in particular through the type of feed consumed by the herds.

Dairy cattle, goat and sheep systems show low levels of gross protein efficiency with, once again, homogeneity between feeding systems: 0.20 in C, 0.15 in G and 0.13 in S (Table 4). This means, for example, that for every 1 kg of plant protein consumed by a herd of dairy goats, only 0.15 kg of protein is available for human consumption via milk and meat products. However, protein efficiency is greatly improved when only the part that can be consumed by humans and is consumed by the herd is taken into account. Dairy systems have net protein efficiencies of 1.88 in C, 1.12 in G and 1.16 in S (Table 4). On average, the systems studied produce more protein for human consumption than they consume. They are therefore net producers of protein for human consumption. On average, BL systems produce 88% more animal protein than they consume in plant protein for human consumption. There is considerable variability within and between systems, which means that technical levers can be identified to further increase net protein efficiency. These variabilities are all the greater when systems use a large proportion of grass (Rouillé et al., 2019).

ENERGY	Number of farms (n)	Energy feed consersion efficiencyEnergy feed consersion efficiency(GEE)	Standard deviation EEB	Edible energy feed consersion efficiency(NEE)	Standard deviation EEN	Energy not consumed by humans (%)
Dairy cattle system						
C-M10-	415	0,12	0,02	1,31	0,49	91%
C-M10+	178	0,14	0,02	0,74	0,18	81%
C-P10-	133	0,11	0,02	2,67	5,61	96%
C-P10+	222	0,15	0,02	0,67	0,16	78%

C-P1030	434	0,14	0,02	0,88	0,31	84%
Weighted average	**1382**	**0,14**	**0,02**	**1,00**	**0,63**	**86%**
Dairy goat systems						
G-CC	52	0,11	0,03	0,51	0,12	78%
G-WG	63	0,10	0,02	0,48	0,11	79%
G-MS	81	0,11	0,03	0,41	0,13	74%
G-MH	102	0,09	0,03	0,58	0,17	84%
G-LH	135	0,09	0,02	0,47	0,11	80%
G-EB	78	0,09	0,03	0,73	0,29	88%
G-EP	113	0,06	0,03	0,59	0,24	89%
G-PM	208	0,09	0,02	0,56	0,22	84%
G-DD	15	0,11	0,03	0,39	0,10	71%
Weighted average	**847**	**0,09**	**0,02**	**0,54**	**0,18**	**83%**
Dairy sheep systems						
S-DC	33	0,06	0,01	0,61	0,32	91%
S-NPA	46	0,08	0,01	0,59	0,19	86%
S-TPA	54	0,06	0,01	0,60	0,20	90%
S-GR	84	0,08	0,01	0,65	0,14	88%
S-MR	126	0,09	0,01	0,67	0,16	87%
Weighted average	**343**	**0,07**	**0,01**	**0,63**	**0,18**	**88%**

Table 3 Gross and edible energy feed consersion efficiencyof dairy systems in France

PROTEIN	Number of employees (n)	Gross Protein Efficiency (GPE)	Standard deviation EPB	Net Protein Efficiency (NPE)	Standard deviation EPN	Protein not suitable for human consumption (%)
Dairy cattle system						
C-M10-	415	0,18	0,03	2,17	1,00	92%
C-M10+	178	0,20	0,03	1,18	0,55	83%
C-P10-	133	0,17	0,03	4,23	6,08	96%
C-P10+	222	0,22	0,03	1,41	1,12	85%
C-P1030	434	0,21	0,04	2,08	1,58	90%
Weighted average	**1382**	**0,20**	**0,03**	**1,88**	**1,45**	**89%**
Dairy goat systems						
G-CC	52	0,17	0,05	1,44	1,79	88%

G-WG	63	0,16	0,04	0,96	0,65	83%
G-MS	81	0,18	0,04	0,74	0,42	76%
G-MH	102	0,15	0,04	1,13	0,53	87%
G-LH	135	0,16	0,03	0,93	0,43	83%
G-EB	78	0,15	0,04	1,48	0,66	90%
G-EP	113	0,11	0,05	1,57	1,35	93%
G-PM	208	0,15	0,04	1,08	0,59	86%
G-DD	15	0,17	0,04	0,66	0,14	74%
Weighted average	**847**	**0,15**	**0,04**	**1,12**	**0,67**	**86%**
Dairy sheep systems						
S-DC	33	0,10	0,02	1,38	0,85	92%
S-NPA	46	0,14	0,02	1,28	0,54	89%
S-TPA	54	0,10	0,02	1,28	0,71	92%
S-GR	84	0,14	0,02	1,02	0,29	86%
S-MR	126	0,15	0,03	1,02	0,47	85%
Weighted average	**343**	**0,13**	**0,02**	**1,16**	**0,54**	**89%**

Table 4 Gross and net protein efficiency of dairy systems in France

3.3 Results from experimental farms confirm national data

For dairy cattle, three sites were evaluated for conversion efficiency at system level: Trévarez Bio, La Blanche Maison and the farm of the Lycée de Saint-Lô-Thère. Table 5 below shows the main results. These systems consume between 5 and 8 kg of crude protein to produce 1 kg of animal protein. However, as most of this protein is not consumed by humans, it only takes 0.2 to 0.8 kg of plant protein consumed by humans to produce 1 kg of animal protein. These systems are therefore net producers of protein (Rouillé et al., 2022).

The same approach applied to energy reveals more nuanced results. The more grass is present in the feed system, the lower the level of competition for energy. For example, to produce 1 kcal of animal origin, the Trévarez organic system consumes 0.7 kcal human-edible.

To produce 1 kg of animal protein...	**Trévarez Organic 2015-2017**	**Trévarez Organic 2018-2020**	**La Blanche Maison**	**Saint-Lô-Thère High School**
...a cow consumes XX kg of vegetable protein	7,5	7,7	5,7	7,9
...one cow consumes XX kg of plant proteins that can be eaten by humans	0,3	0,2	0,2	0,8
To produce 1 kcal of animal origin...				
...a cow consumes XX kcal of plant matter	7,9	8,0	9,5	12,1
...a cow consumes XX kcal of plant matter that can be used by humans	0,7	0,7	1,0	1,5

Table 5: Protein and energy efficiency of experimental systems

For dairy goats, two sites were involved: EPL Aubenas and the Patuchev system (INRAE UE FERLus). It was decided to study one of the goat herds in the Patuchev experiment-system with farrowings in February and maximising the use of pasture over the period 2016 to 2018 (Kocken et al., 2020). Protein and energy efficiency indicators were calculated from data recorded in the Diapason database for a herd of 63 Alpine dairy goats with an average annual production of 702 litres per goat, 25 kids and 5 bucks. Energy feed consersion efficiencyEnergy feed consersion efficiencyaveraged 0.10 and gross protein efficiency 0.18. 82% of the protein and 81% of the energy consumed by the herd was not human-edible. Net protein efficiency averaged 1.02 and improved significantly over the campaigns. By choosing to improve feed self-sufficiency and limit concentrate intake, this type of management, which mainly uses grass for grazing, improves its protein and energy efficiency. However, the improvement in milk production per goat over the seasons shows the importance of this criterion for a better level of efficiency. Beyond the quantitative aspects, it is also important to pay attention to the characteristics of the feedstuffs chosen, such as the composition of feedstuffs in reduced competition with human nutrition (-22% of concentrates with a proportion of human-edible protein >60% between 2016 and 2018), the energy and protein quality of forages (only 13% MAT on average in 2017), and to ensure that the whole grains of the meslin distributed to the goats are properly utilised, as they are in greater competition with concentrates made up of co-products.

For the Aubenas EPL, evaluation of the complete system showed results close to those obtained at national level. Energy feed consersion efficiencyEnergy feed consersion efficiencyaveraged 0.17 and gross protein efficiency 0.14. 87% of the protein and 83% of the energy consumed by the herd was not human-edible. Net protein efficiency averaged 1.3, making the system a net producer of protein.

In addition, calculations were carried out on daily rations to assess 'instantaneous' efficiency. This approach was not part of the core project, but it enabled us to assess the effect of nitrogen supplementation and grazing methods on the animals' conversion efficiency.

The Saint-Affrique dairy sheep farm has set up a trial to test the effect of a ration that does not compete with human feed on dairy ewes by replacing cereals with beet pulp and spent grain, by-products that cannot be consumed by humans. Evaluation of this instantaneous efficiency has shown that it is possible to feed ewes a ration that competes very little with human feed without any loss in the quantity or quality of milk produced. In particular, some ewes ingested over 300g more DM (dry matter) per day without producing more milk. Lastly, as well as showing that milk production was not affected, the ration studied also proved favourable to lowering the average urea content of the milk (444 vs 533 mg/l), and therefore to better nitrogen utilisation (Fança et al., 2020).

3.4 Innovation groups that have adopted the method and the results

Four innovation groups met throughout the project to learn about the methodologies used and the results, and to discuss their interpretation and use. The innovation groups are multidisciplinary groups organised by dairy sector. They provided an opportunity to discuss the understanding of the competition in use dealt with in the project, to clarify the methodology used and to popularise the concept and the results.

It was these innovation *groups* that proposed and validated the formulas used to express the results clearly. Here is an example of the net approach:

"To produce 1 kg of animal protein/1 kcal for human consumption, a cow consumes XX kg of plant protein/XX kcal for human consumption".

3.5 A range of communication media and channels

All the results have been communicated extensively. A wide range of materials have been created for different audiences and can be accessed here: https://idele.fr/eradal/

The list of media and channels is as follows:

- Motion design films

- Commented slideshows
- A game of 6 families
- A positioning tool for breeders
- Social networks #ERADAL
- Communications in the agricultural press and the general public press
- Agricultural shows
- French and European conferences

Photo 1: Game of 6 families on food competition

4. Discussion

The energy and protein efficiency figures for French dairy systems are in line with those presented recently (Laisse et al., 2016; Laisse et al., 2018). There is a hierarchy linked in particular to the proportion of grass used in rations, and more generally to feedstuffs that compete little or not at all with human food. These figures show that ruminants are efficient at transforming plants into animal products that can be used by humans.

Other studies have led to the use of feedstuffs previously consumed by ruminants for human consumption. Wilkinson (2011) has proposed a 'potential' scenario that anticipates better use of raw materials for human consumption. Ruminant systems would see increased competition for plant resources. Efficiencies would deteriorate for all systems. A high proportion of grass helps to maintain the system's efficiency (Laisse et al., 2018). The potential use of proteins from oilcake in human food is difficult to predict and remains a question for the future.

Although dairy ruminants are efficient at using resources that cannot be consumed by humans, they are in competition for land. Worldwide, livestock farming consumes 32% of grain, 40% of arable land and 700 million hectares of potentially arable grassland (Mottet et al., 2017). In France, this mainly concerns lowland dairy cattle systems where arable land is used for silage maize, meslin or temporary grassland. Mountain systems with permanent grassland face little or no competition in this respect. France has 28 million hectares of agricultural land. Around 18 million hectares are used for animal feed (64%) (Agreste, 2013). Of these 18 million hectares, 14 million are used for fodder crops, including 9.8 million hectares of non-arable land. Reallocating arable land used for livestock farming (8.2 million ha) to human plant-based food raises the question of how to manage this land and its yields, and how to intensify livestock production. The CASDAR ERADAL project is paying particular attention to this approach, in particular using the Land Use Ratio (LUR) proposed by Van Zanten et al (2016). This indicator focuses on protein that can be digested by humans, and will make it possible to compare the actual production of animal protein on a farm with the potential production of plant protein if stopping livestock farming makes it possible to return the land freed up to crops for human consumption.

Finally, co-products from the French agri-food industries now account for 12 million tonnes DM, 76% of which is recovered by animal feed (RESEDA, 2018). Ruminant industries are therefore at the heart of the circular economy by effectively recovering co-products from human food. And from these co-products, they again supply this human food with proteins of high nutritional value. These proteins are better balanced in terms of essential amino acids and therefore have a better DIAAS (Digestible Indispensable Amino Acid Score) score (FAO, 2013).

5. Conclusion

The ERADAL project has made it possible to characterise a wide range of dairy cattle, sheep and goat systems in terms of their ability to transform the energy and protein in their feed into animal products for human consumption. Although the gross efficiencies are low, the net approach has enabled us to confirm that, on average, these systems are net consumers of energy and net producers of protein. This is a major challenge for the future of ruminant systems, in order to address the issue of competition between animal feed and human food.

However, there is considerable intra-system variability, particularly in the net approach. This makes it possible to identify avenues for improvement via the choice of feed (forages and concentrates) or the system's ability to produce more by consuming the same or less.

To complete the approach, competition in the use of land and the nutritional quality of the animal proteins produced will need to be addressed in further work.

Ethics
The authors declare that the experiments were carried out in compliance with the applicable national regulations.

Declaration on the availability of data and models
The data supporting the results presented in this article are available on request from the author of the article.

Declaration on Generative Artificial Intelligence and Artificial Intelligence Assisted Technologies in the Drafting Process.
The authors have used artificial intelligence-assisted technologies to translate from French to English.

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Declaration of interest
The authors declare that they do not work for, advise, own shares in, or receive funds from any organisation that could benefit from this article, and declare no affiliation other than those listed at the beginning of the article.

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