A comparison of animal and plant-based proteins from an economic, environmental, and nutritional perspective in the Republic of Ireland

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Abstract

Protein is a central component of health and nutrition. The current animal protein production systems might not be able meet this growing demand for food and protein while also meeting climate change policy commitments. Therefore, alternative sources of protein must be considered. This study uniquely compares animal-based protein sources (milk, beef, sheep meat) to plant-based protein (wheat, barley, oats) across a suite of economic, environmental, and nutritional metrics. Economic performance is measured through the gross margin earned by the farmer, environmental performance through the farm-level CO_2 emissions, and the nutritional performance through the gross protein yield and the protein yield corrected for digestibility using the Digestible Indispensable Amino Acid Score (DIAAS). Findings indicate that cereal crops perform better in terms of environmental and nutritional aspects but lag significantly behind the best economically performing livestock-based system, dairying. Moreover, dairy farms produce less gross protein than crop-specialized farms, but they produce a similar amount of available protein on a per hectare basis, i.e., protein that can be utilized by the body after digestion. The results do not allow for a definitive answer as to which protein source is the most holistically sustainable as the relative efficiency depends on the metric considered.

Keywords Agricultural Economics; protein efficiency; crops; livestock farming

JEL code Q18: Agricultural Policy; Food Policy; Animal Welfare Policy

1.0 Introduction

The world's population is expected to reach between 8.5 and 8.6 billion people by 2030 (UN, 2019). As a result, the global demand for food is expected to grow by 1.3% per annum by 2030 (OECD/FAO, 2021). The importance of a safe, nutritious and an affordable supply of food for global health is unquestionable. However, the potential negative impact of food production on the environment remains one of the greatest global challenges. Proteins are a central component of health and nutrition; they contribute to key human physical processes such as growth, development, maintenance, tissue repair, enzyme production and hormone performance (FAO, 2021). Given that, on average, more than half of all protein consumed in the world is derived from animal products and that animals are a major contributor to global warming, protein production will become a central part of the challenge, that is, sustainably feeding the world's growing population (OECD/FAO, 2021). Indeed, the current production systems, which mostly focus on livestock production, might not be able to meet the growing demand for food and protein in a sustainable way.

A shift away from animal towards more plant-based protein consumption and production has several potential environmental benefits in order to meet the growing food and protein demand. However, the commercial viability of such a shift also needs to be considered, as does the profitability at the farm level if land use change is to occur. Furthermore, the nutritional impacts of substituting plant for animal-based proteins needs to be considered as plant proteins may not have the same biological, physiological and health-promoting properties and might not be processed in the same way by the human body.

More specifically, this paper examines the following research questions: how do plant-based proteins compare with animal on a suite of economic, environmental, and nutritional metrics? Furthermore, if plant-based proteins are more environmentally sustainable and are nutritionally equivalent or superior to animal proteins, what policy or market levers are required to incentivise farmers to shift production away from livestock systems?

The next section provides a contextual background to the research question. The third section presents the methodology and data used, while results are presented in the fourth section. In the concluding sections of the paper the results are discussed in depth and some policy implications are explored.

2.0 Contextual background

In response to the many challenges of feeding the world's growing population, the EAT-Lancet report (The Lancet Commissions, 2019) proposed a sustainable diet which respects the planet boundaries as defined by Röckstrom (Rockström et al., 2009). This diet encompasses the Paris Agreement's main target, i.e., "*limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels*" (UNFCCC, 2022), as well as meeting human health requirements, while also considering the feasibility of production to feed the world's 10 billion people as predicted by the UN. The gaps between the EAT-Lancet recommended diet and the current global diet are most striking when looking at protein sources.

Indeed, the food group that is exceeding the recommended dietary thresholds the most is red meat, whereas the food groups for which consumption is the lowest in comparison to the recommended thresholds are legumes, whole grains and nuts, the three main plant-based protein sources. When looking at the European case, the over-consumption of animal-based proteins, in particular that of red meat, can be explained by several factors. These include, for example, higher levels of disposable income and changes in trade policy that facilitated the import of soy as feed for livestock conferring on animal-based production a comparative advantage over crops production (Watson, et al., 2017). Furthermore, the European Common Agricultural Policy (CAP) also contributed to the overproduction of agricultural commodities, including beef and dairy, mainly through the structure of its payment systems (Barnes et al., 2016).

From an economic perspective, we can observe a trend towards the development of the market for meat alternatives. For example, in the Netherlands, since the middle of the 2000s, there is an observed trend towards a higher consumption of plant-based meat substitutes. This has emanated from an increasing awareness of the environmental impacts of meat and livestock production (Tziva et al., 2019) as well as from concerns about the effects of meat consumption on health (Freedman et al., 2010). Plant-based diets are associated with several positive characteristics such as "*healthy*", "*sustainable*" and "*nutritious*" (Van Loo et al., 2017).

On the environmental side, livestock production can be associated with many negative impacts. Several comparisons have been performed between selected sources of animal and plant-based proteins over the years. There is a significant gap between the carbon footprint of proteins derived from livestock products and that of plant-based proteins. For example, per 54 calories, the CO_2 emissions from cow milk's was more than 3 times higher than that of the plant-based substitutes (Detzel et al., 2022). Furthermore, a kilogram of beef protein was found to use 8 times more fuel, 10 times more water and pesticides, 12 times more fertiliser and 18 times more land than a kilogram of kidney beans (Sabaté et al., 2014). Notably, the Sabaté et al., (2014) study did not compare the nutritional value of beef and kidney beans. Concerns regarding the sustainability of livestock production also include the rise in competition between feed and food production. A study across 16 European beef farms operating under different systems found that only one of them produced more human edible energy than it consumed (Mosnier et al., 2021).

While the studies cited above compared food products on their environmental impacts, it is also important to compare the nutritional value of the products. Animal and plant-based proteins can have different compositions, which result in differences in terms of their human nutrition and health impacts. Three important metrics used to evaluate the nutritional aspects of protein are its protein content, amino acid content and the digestibility of the proteins (Day et al., 2022). Amino acids are the molecules remaining after the protein has been digested and are used by the human body for processes such as growth, nutrient transport, repair and hormone development. The most important type of amino acid to consider when looking at the quality of proteins is essential amino acids; these cannot be produced by the human body and must come from the diet. Several studies found that animal protein sources are generally richer in amino acids, both essential and non-essential, compared to plant-based protein sources (Gorissen et al., 2018; Day et al., 2022).

Overall, most comparisons between animal and plant-based proteins focus on the quantity of protein derived from both types. Some studies look at the quality of the protein, but very few studies combine both aspects, and fewer still include economic and environmental considerations. Table 5 in appendix 1 reviews indicators from different studies which have assessed different elements of protein performances whether from an economic, environmental or nutritional perspective. As outlined in Table 5, this study is unique as it aims to investigate economic, environmental and nutritional aspects (quality and quantity) of different protein sources simultaneously.

Several methods exist to determine the overall quality of protein, as well as the digestibility (Adhikari et al., 2022). The FAO developed two main methods, the DIAAS (Digestible Indispensable Amino Acid Score) and the PDCAAS (Protein Digestibility-Corrected Amino Acid Score). Developed more recently, the DIAAS is promoted by the FAO as the preferred metric (FAO, 2013). The DIAAS compares, for each indispensable amino acid, the amount of amino acid digested by the body with the reference intake requirement of the amino acid. Of all the values, the lowest is considered as the final score. This method encompasses several aspects of protein quality evaluation: the amino acid content, the digestibility of these amino acids and the first limiting amino acid. This is the amino acid present in the least amount compared to the reference requirements for amino acid intake. The DIAAS is generally higher for animal-based protein sources than for plant-based sources, indicating a higher quality and digestibility for the former group (Day et al., 2022).

This again raises the question of whether plant-based proteins are more sustainable than animal-based proteins in all relevant aspects, i.e., economically, environmentally, and nutritionally.

This paper uses data from the Republic of Ireland (labelled Ireland henceforth) to address this research question. Although a small country, Ireland is an interesting case-study due to the size of its agricultural sector, the dominance of livestock-based agriculture over plant-based systems of production and the significant volume of agri-food exports from Ireland each year. In 2020, Ireland was the seventh largest exporter of beef in the world with 325,729 tonnes exported (FAO, 2022). In 2020, 10.8% of the total beef production, 14.2% of the total sheep meat production and 5.9% of the total milk production in the European Union originated from Ireland (Eurostat, 2021a). However, the country accounts for only 2.8% of the GDP of the EU-27 (Eurostat, 2022a) and 1.1% of the EU-27's total population (Eurostat, 2022b).

Table 1 shows that the Irish agricultural sector is largely based on cattle rearing/fattening and milk production, whereas across the European Union the agricultural sector is more arable oriented. The relative contribution of agriculture to GHG emissions is much higher in Ireland compared to the European average. In order to meet the national targets set out in the Government's Climate Action Plan 2021, approved by the Irish House of Representatives in June 2021, Irish agricultural emissions should decrease by 25% by 2030 compared to 2018's reference levels (Government of Ireland, 2022). According to the latest projections for 2030, said emissions would be reduced by only 0.8% with existing measures and by 22.4% with additional measures (EPA, 2022).

Table 1: Sectoral agriculture repartition and impact of agriculture on GHG emissions in Ireland and the EU

	Ireland	European Union
Farms specialized in cattle rearing and fattening (2016)[1]	53%	3.9%
Farms specialized in cereals, oilseed, and protein crops (2016)[1]	3%	15.2%
Farms specialized in field cropping (2016)[1]	6.1%	16.4%
Farms specialized in dairy (2016)[1]	12.1%	5.4%
Share of agriculture in total GHG emissions (2020)[2]	35.2%	11.4%
Share of agriculture in total CH_4 emissions (2020)[2]	93.1%	55.4%

Share of agriculture in total N_2O emissions (2020)[2]	92.5%	80.1%

[1]Eurostat, 2021b; [2]Eurostat, 2022c

In terms of the potential substitution between livestock and crop-based agriculture, the soil and associated land use potential must be considered. In Ireland, 23.4% of the land was classified as having a "*wide use range*" and 11.7% as having a "*moderately wide use range*" (Gardiner and Radford, 1980). Furthermore, 50.1% of soils in Ireland were classified as suitable for tillage. In all, 14.7% of Irish soils were labelled as highly suitable. Such soils are favourable to crops such as malting barley, wheat, or root crops.

3.0 Methodology

In this paper, indicators of economic, environmental and nutritional performance are developed for livestock and crop enterprises using data for Ireland. The following sections outline the approach to indicator development and the data used in this analysis.

3.1 The indicators

This analysis compares animal and plant-based proteins using economic, environmental and nutritional indicators. The economic aspect is measured by the gross margin in euros, which is calculated by subtracting the direct costs of the relevant farm enterprise from the associated market based gross output. This means that subsidies and overhead costs are not included. For cereals, the gross margin derived from straw is included. The environmental impact is measured by the total GHG emissions in kg of CO_2 equivalent for the product under consideration. The GHG emissions are calculated according to the IPCC methodology, as previously published by Buckley and Donnellan, (2022). The nutritional aspect is evaluated using the gross protein yield and the protein yield corrected for digestibility using the DIAAS value of each protein source, as suggested by Moughan (2021). This allows for an evaluation of the amount of protein produced that can be used by the body during and after the digestion process. To do so, the protein yield is multiplied by the DIAAS score. When the DIAAS score is higher than 100%, the value is truncated to 100%, following the FAO guidelines (2013).

Indicators are expressed per hectare, per 100 g of gross protein, and per 100g of digestible protein, to present the efficiency of the different protein sources considered. Results are derived by unit of product (e.g., kg). The types of livestock protein sources considered are beef, sheep and milk. The plant-based protein sources examined are winter oats, spring oats, winter wheat, winter barley and spring barley. The protein sources were chosen depending on the availability of agronomic data.

3.2 The data

The economic and environmental indicators are developed using data from the Teagasc National Farm Survey 2020 (NFS). The NFS is part of the European Union Farm Accountancy Data Network (FADN), a network monitored by the European Commission which gathers data on the economic performance of farms across the European Union. The analysis can then be replicated for other EU member states. Data was collected by a team of trained farm data recorders from 812 nationally representative farms in 2020. The NFS dataset gives a population weight to each farm to make them representative of a given number of farms in the national population based on farm size and system type. This way, the sample of 812 farms becomes a representation of more than circa 90,000 farmers in the national population of nearly 140,000 (CSO, 2017). The data for protein yields come from several sources. The protein contents of the products are taken from the 2020 CIQUAL table developed by the French *Agence nationale de sécurité sanitaire de l'alimentation* (ANSES, 2020). The carcass and dry matter coefficients come from several publications (Teagasc Animal and Grassland Research and Innovation Programme, 2015; Schweihofer, 2011; NFS, 2021). Data for the DIAAS values is taken from the work conducted by Ertl et al. (2016).

Farms are separated according to their farm system as defined by FADN-based typology rules, e.g., for evaluation of milk protein specialist dairy farms are considered, for beef production cattle farms, etc (for a more detailed breakdown of the typologies please refer to Dillon et al (2021)). The sample considered here consists of 341 cattle farms, 290 dairy farms, 81 sheep farms, 15 arable farms with winter oats, 25 arable farms with spring oats, 22 arable farms with winter wheat, 33 arable farms with winter barley and 72 arable farms with spring barley. Only lowland sheep farms are considered to avoid a potential distortion of the results arising from hill sheep farms being extensive systems with low inputs and low yields.

In order to compute the per hectare variables for livestock production systems, the area allocated to the type of livestock considered was calculated. Indeed, a farm can be specialized in beef production, for example, but also produce sheep meat as a subsidiary enterprise. The number of hectares allocated to beef would then be overestimated if considering only the utilized agricultural area as such. The area allocated was then computed as follows:

$$Area\ allocated\ in\ HA_{i,j} = (UAA_i - Arable\ non\ fodder\ area_i) * (Livestock\ Units_j\ /\ Total\ Livestock\ Unit_i$$

Where *i* is the farm and *j* the livestock type considered.

The quantity of protein produced by beef and sheep farms is computed as follows:

$$Protein_j = Offtake\ of\ liveweight_j \times average\ carcass\ meat\ yield\ \%_j \times protein\ coefficient_j$$

Where *j* is the livestock type considered.

For milk, the data is directly recorded in the NFS as dairy farmers are paid on the basis of milk solids composition. Hence, for dairy farms the protein content per litre of milk produced is recorded for each farm in the survey. The average protein content across the dairy farm sample in 2020 was 3.5% per kilogram of milk delivered.

The quantity of protein produced for crops is computed as follows:

$$Protein_k = dry\ matter\ yield_k \times protein\ coefficient_k$$

Where *k* is the crop considered.

Table 2 presents the coefficient used in the formulas above as well as the DIAAS and PDCAAS value for each protein source considered.

Table 2: Coefficients for nutrition indicators

	Beef	Sheep	Oats	Wheat	Barley	Milk
Protein content (in g / 100 g of product)	19.98[2]	18.1[2]	16.9[2]	10.98[2]	12.5[2]	3.5[1]

DIAAS[3] (%)	109.3	116.8	56.7	40.2	47.2	115.9

[1]NFS, 2021; [2]ANSES, 2020; [3]Ertl, Steinwidder et al., 2016

4.0 Results

This section presents economic, environmental and nutritional indicator data on a per hectare and protein yield (per 100 g of product) basis.

4.1 Economic, environmental and nutrition indicators on a per hectare basis

Table 3 presents the relevant variables per hectare for each system of production. On a per hectare basis, dairying (milk production) is the most profitable, with a gross margin of €2,538 per hectare compared to less than €1,200 for all other products. However, dairy farms have the highest level of GHG emissions at 9,839 kg of CO_2 equivalent emitted per hectare. This is over twice the emissions of the next closest farm systems (cattle farming at 4,414 kg of CO_2 equivalent).

Cattle and sheep farms have lower levels of gross margin per hectare compared to crop-specialized farms, and they have comparable or higher levels of GHG emissions per hectare. Amongst the plant-based protein sources, winter crops have a higher gross margin per hectare compared to spring crops. However, they also have a higher level of GHG emissions. Indeed, winter crops are generally more demanding in terms of fertilizer inputs than spring crops (Collins and Phelan, 2022).

Table 3: Production systems' performances per hectare

System of production	Gross Margin per Hectare (€)	GHG emissions per Hectare (kg CO_2 eq. ha^{-1})	Gross protein yield per Hectare (kgs. ha^{-1})	Digestible protein yield per Hectare (kgs. ha^{-1})
Dairy [a]	2538 [b,c,d,e,f,g,h]	9839 [b,c,d,e,f,g,h]	411 [b,c,d,e,f,g,h]	411 [b,c,d,e,g,h]
Lowland Sheep [b]	431[a,d]	2662 [a]	31 [a,d,e,f,g,h]	31 [a,d,e,f,g,h]
Cattle [c]	400[a,d]	4414 [a,b,f,g,h]	46 [a,d,e,f,g,h]	46 [a,d,e,f,g,h]
Winter Wheat [d]	1123 [a,b,c]	2976 [a]	820 [a,b,c,e,h]	330 [a,b,c,e,g]

Winter Oats [e]	747 [a]	2881 [a]	1132 [a,b,c,d,f,g,h]	642 [a,b,c,d,f,g,h]
Winter Barley [f]	719 [a]	2332 [a,c]	853 [a,b,c,e,h]	402 [b,c,e,g]
Spring Oats [g]	706 [a]	1627 [a,c]	903 [a,b,c,e,h]	512 [a,b,c,d,e,f,h]
Spring Barley [h]	641 [a,d]	1763 [a,c]	728 [a,b,c,d,e,f,g]	344 [a,b,c,e,g]

Results are rounded up for clarity; subscript letters are used to denote statistically significant differences. Statistical differences are investigated using the Tuckey post hoc test. A difference is considered statistically significant if $p < 0.05$.

Furthermore, on average, crop-specialized farms produce more gross protein per hectare than farms specialized in livestock. Indeed, cattle and sheep-specialized farms produce on average less than 50 kg of protein per hectare, whereas crop-specialized farms all produce more than 700 kg of protein per hectare. Dairy-specialized farms produce 411 kg of protein per hectare, making them the best performing livestock system, but still below crop-based farms. This could be because for cereals products, more than 85% of the total yield can be converted into food (i.e., dry matter), whereas out of the total sheep and cattle production, circa 50% can be converted into food (i.e., carcass). Amongst cereals, winter oats produce the highest level of gross protein per hectare at 1,132 kg.

However, when considering the available-protein yield, cereals become less efficient. The DIAAS score is equal to or greater than 100% for all three animal-protein sources, which means that the proteins and amino acids in these products are highly available to the human body and the first limiting amino acid is present in a quantity lower than or equal to the recommended reference intake level. The DIAAS for the crops examined here were all lower than 100% (between 40 and 57%). On a per hectare basis, crops-specialized farms still produce more available protein than cattle and lowland sheep farms, but dairy farms' available protein yield is now in a similar range to that of cereals production.

4.2 Economic, environmental and nutritional indicators on a per yield of gross and available protein basis

Table 4 presents the gross margin and the GHG emissions per 100 g of gross protein produced and per 100 g of digestible protein. When considering the results per 100 g of protein instead of per hectare, the relative efficiency changes. Lowland sheep meat becomes the most economically efficient and is the only product with a gross margin per 100 g of protein higher than one euro. However, this is not due to a high absolute gross margin (the absolute gross margin of sheep-specialized farms is only the fifth highest of all products considered) but to a low overall protein yield in sheep-specialized farms (sheep-specialized farms have the lowest gross protein yield out of all farm systems. Sheep meat production from lowland farms is also associated with the highest GHG emissions at 15.2 kilograms of CO_2 equivalent per 100 g of gross protein. Again, this is not due to a high level of gross GHG emissions, but to a low overall protein yield. Moreover, sheep output prices were historically high in 2020, compared to previous years and to other animal output prices (CSO, 2022a).

The main change between the results expressed per hectare and the results expressed per 100 g of protein is the relative efficiency of cereals compared to livestock products. Here, cereal products are more environmentally efficient but less economically efficient than all livestock products. For 100 g of gross protein from beef and milk, farmers earn €0.87 and €0.62 respectively. This compares to less than €0.16 for all cereal-based products. However, crop farms produce significantly more gross protein than livestock farms which could potentially compensate the gap in gross margin. Farms specialized in livestock still have higher levels of GHG emissions per 100 g of gross protein produced compared to all cereal crops examined. Results indicate GHG emissions above 2 kilogrammes of CO_2 equivalent for 100 g of gross protein for all livestock produced, while all cereals-based products emissions are below 0.5 kilogrammes.

When expressed per 100 g of available protein instead of per 100 g of gross protein produced, cereals are still significantly less economically efficient than livestock products. However, the absolute gross margin return is higher on per 100 g of available protein versus gross protein as gross margin is distributed across a lower yield of protein. Winter wheat is still the best performing cereal, but the gross margin per 100 g of available protein produced is half that of the lowest performing animal-based protein source of milk. The other plant-based protein sources all have a gross margin per 100 g of available protein of between €0.1 and €0.2, which is 3 times lower than milk, 4 times lower than beef meat, and 7 times lower than sheep meat. What is also noticeable is the relative environmental efficiency change of cereals when examined per 100 g of available versus gross protein. Winter wheat now emits more than one kilogram of GHG per 100 g of available protein, which is only half that of milk (against five times less when expressed in terms of gross protein). Livestock protein sources still emit more GHG than crops on this metric, but they are also still much more economically efficient.

Table 4: Economic and environmental performances per 100 grams of gross protein and digestible protein

System of production	Gross Margin per 100 g of gross protein (€)	GHG emissions per 100 g of gross protein (kg CO_2 eq.)	Gross Margin per 100 g of digestible protein (€)	GHG emissions per 100 g of digestible protein (kg CO_2 eq.)
Lowland Sheep	1.49	15.24	1.49	15.24
Cattle	.87	10.93	.87	10.93
Dairy	.62	2.51	.62	2.51
Winter Wheat	.16	.45	.40	1.12
Spring Oats	.09	.15	.17	.27
Spring Barley	.09	.24	.19	.51
Winter Barley	.08	.28	.17	.60
Winter Oats	.06	.25	.11	.43

Results are rounded up for clarity

In summary, dairy is the most profitable yet most GHG emitting production system per hectare. Its nutritional performances are mixed, with a lower yield of gross protein but a similar digestible protein yield compared to cereals. Sheep and beef meet have poor economic and nutritional performances, and similar or poorer environmental performances compared to cereals. Winter cereals have the best economic performances amongst crops but also the poorest environmental results.

Per 100 g of protein, sheep and beef meat have better relative economic performances but they also generate higher GHG emissions compared to other systems. Milk also generates higher GHG emissions per 100 g of protein than crops, but to a lesser extent. Overall, the crops examined emit less CO_2 per hectare and per 100 g of protein, but from the farmers' perspective they are also less profitable than dairying.

5.0 Policy implications

This research aims to compare farm level protein production systems across economic, environmental and nutritional dimensions. Findings indicate that the cereal crops examined here perform better in terms of environmental and nutritional aspects but lag significantly behind the best economically performing livestock-based system, dairying. When looking at protein yields, dairy farms produce less gross protein than crops-specialized farms, but they produce a similar amount of available protein on a per hectare basis. Producing beef and sheep meat production is environmentally less efficient than producing cereals. Economically, producing beef and sheep is either comparable or less efficient than producing cereal.

Given the growing need to tackle climate change while maintaining global food security, policy makers are faced with difficult decisions and the results presented here re-enforce the complexity faced. For example, based on the data presented here, if policy makers decide to promote the substitution of land used for livestock production into crop production, there would be implications for the availability of protein and the viability of farming. A switch towards spring oats production for example, would be the least GHG emitting plant-based protein source per hectare, a switch to winter wheat production would lead to the most profitable plant-based protein source per hectare while a switch towards winter oats would result in the highest protein yield per hectare.

The most efficient change from the perspective of reducing GHG emissions and optimising on protein yield, i.e., tackling climate change while maintaining food security, would indicate a land use change from dairy towards winter oats production. Under this scenario, GHG emissions would decrease by 71%, while gross protein yield would increase by 175% and available protein yield by 56%. However, this would imply a 71% reduction in gross margin per hectare, clearly pointing to the need for policy makers and/or industry to introduce financial incentives if they wish to promote this kind of land use change.

The EAT-Lancet report (The Lancet Commissions, 2019) reference diet can be used as a basis to identify optimal land use change. If the reference diet were to be fully adopted globally and combined with the scenario where food waste is dramatically decreased, beef production would decrease by about 60%, and wheat production would increase by about 40%. If we translate those projections into this farm level analysis, a transition from beef production towards winter wheat would result in a decrease of GHG emissions per hectare by 33%, and an increase in available protein yield by 621%. Gross margin at farm level would increase by 181%. This is assuming that the biophysical environment could support the growing of this crop in the first instance. The complete set of results can be found in Table 6 in appendix 2.

Economically, shifting production away from beef and sheep would give the opportunity of a gross margin increase, a so-called win-win scenario. However, shifting production away from dairy towards crops would cause a considerable reduction in gross margin for farmers. This suggests that policy makers need to consider both non-monetary and monetary incentives to promote such land use changes.

Reflective of many decades of direct payments and subsidies for livestock production, beef production is the predominant farming system in Ireland and a transition to crop production would require considerable adjustment. First, farmers are constrained by the biophysical characteristics of their land. As mentioned previously, half of the Irish territory is deemed suitable for tillage, but only about 15% is estimated to be highly suitable. Hence, transition from one system to another is not always possible, or in some cases would not be very efficient. Second, changing production systems requires new knowledge and skills, especially considering the very different characteristics between growing crops and producing livestock. Substitution from livestock production to arable crop production might also require significant capital investment from farmers, access to this capital could be a constraining factor. Additionally, farmers might not be willing to learn the set of skills necessary to make the change, especially if they are towards the end of their career and would see it as too much of an effort. This could be especially relevant in Ireland where, in 2020, about 58% of Irish farmers are 55 years old or older (CSO, 2022b). Moreover, converting grassland into arable cropland could have potential negative effects on water quality and biodiversity, as ploughing could lead to nitrogen leaching into ground water or loss of habitats. Those aspects were not considered in this analysis, as only the agricultural-based GHG emissions were used for evaluating the environmental effects of a land use conversion.

Furthermore, the possible lack of market opportunities needs to be considered. Indeed, in the event there was a substantial shift away from animal-based protein production towards more plant-based protein production, processing capacity and market outlets would be needed which might not exist in sufficient degree yet.

On the crop protein side, there are also opportunities for arable crops production in terms of potential improvements to both quality and economic returns. One such opportunity is the ongoing research aimed at upscaling the production of plant-based protein in the value chain. This would enable crop producers to sell products with a higher value-added potential and would return a higher margin compared to that from traditional cereals supply chain channels. Examples of this include protein enriched flours, protein concentrates and isolates, as opposed to the more traditional whole grains and flours. The higher protein content of such fractions and ingredients opens up additional value-add opportunities for use in premium nutritional applications. Indeed, the downstream processing to convert these flours into high protein content concentrates and isolates is generally a prerequisite for their use in premium nutritional applications, due to the requirement to reduce the levels of starch and other non-protein components. Another advantage of processing flours to enrich the protein fraction is that it helps to reduce/eliminate anti-nutrients, thereby helping to improve protein digestibility (Das et al., 2022; Mohapatra et al., 2019).

However, to profit from those opportunities, farmers must have access to the appropriate supply chains and intermediaries. Several organisations, including farmer-owned co-operatives, originally focused on dairy products are now developing new plant-based ingredients and products, such as Tirlan in Ireland or Valio in Finland. This could represent an advantage in a potential transition from one market segment to the other if farmers are already in contact with the appropriate actors.

Recent technological improvements already contribute to making cereal crops more profitable for farmers. For example, the use of genetic engineering, a way to control which traits to keep or to eliminate in a crop, on a selected variety of crops increased agricultural revenues by $57 billion in 2016 across all countries (Scheitrum et al., 2020). Such opportunities for farmers can help to compensate the gap in gross margin between dairy products, for example, and crops.

Financial incentives and disincentives could also be used as policy solutions. In 2020, subsidies and direct payments represented 39% of cattle rearing farms' gross output and 36% of sheep farms' gross output in Ireland on average (Dillon et al., 2021). A change in subsidy regime for livestock farms might help to promote land use change in Ireland. Subsidies could also be re-directed towards plant-based protein production to incentivize further the changes. Penalties could be designed to sanction livestock production. For example, a pricing system targeting methane emissions from agriculture is currently being examined in New Zealand (Government of New Zealand, 2022). Such a system could encourage shifts in production to a more arable based system of production, assuming the processing capacities and market opportunities exist.

In terms of crop production, farms in the European Union face regulations in relation to agricultural methods and the use of new technology. The EU has aggressive targets when it comes to GHG emissions reduction and for reduction of chemical fertilizers use in the agricultural sector. For example, the Farm to Fork Strategy has the objective of reducing the use of fertilizers by 20% by 2030 (European Commission, 2021). This increases pressure on farmers to comply with stringent regulations which differ worldwide.

6.0 Conclusion

This paper compared three animal-based and five plant-based protein sources in terms of economic returns, greenhouse gas emissions and human nutrition. Results do not allow for a definitive answer as to which protein source is the most efficient overall. Relative efficiency depends on the metric considered. From an economic perspective, milk production performs better than all other protein sources on a per hectare basis. Greenhouse gas emissions are much higher for animal-based protein compared to plant-based protein, whether we are analysing the results per hectare, per 100 g of gross protein or per 100 g of available protein. From a nutrition perspective, crops yield a higher quantity of gross protein and of available protein than beef and sheep meat. The yield of gross protein is also higher for crops compared to milk, but the yield of available protein for cereals and milk is somewhat comparable.

A switch away from animal-based protein towards plant-based protein production is one potential pathway to sustainably feed a growing global population. However, economic incentives will be needed to make the change profitable, or at least profit-neutral, for some farmers (especially dairy farms). Non-economic factors will also need to be considered when policies are put in place regarding such a transition.

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Appendix 1

Table 5: Review of existing economic, environmental, and nutritional indicators for protein sources performances

Authors	Indicator(s)	Economic aspect	Environmental aspect	Nutritional aspect	
				Protein quantity	*Protein quality*
Adhikari et al. (2022)	- DIAAS - First limiting indispensable AA - Standardized ileal digestibility of the first limiting indispensable AA (%)	NO	NO	NO	YES
Day et al. (2022)	- Protein content (%) - EAA profile (mg / g of protein) - DIAAS - PDCAAS - Limiting EAA	NO	NO	YES	YES
Detzel et al. (2022)	- GHG emissions (g CO_2 eq. / 100g of product) - GHG emissions (g CO_2 eq. / 30g of protein) - GHG emissions (g CO_2 eq. / 54 kcal) - Environmental footprint (using 12 environmental indicators / 100g of product)	NO	YES	YES	NO
Gonzàlez et al. (2011)	- Protein content (g protein / kg food) - Energy use (MJ / kg) - GHG emissions (kg CO_2 eq. / kg) - Protein delivery efficiency energy (g protein / MJ)	NO	YES	YES	NO

	- Protein delivery efficiency GHG (g protein / kg CO_2 eq.)				
Gorissen et al. (2018)	- Protein content (%) - EAA (% of total protein) - Leucine, isoleucine, valine, lysine, methionine, histidine, threonine content (% of total protein)	NO	NO	YES	YES
Mosnier et al. (2021)	- Human edible protein in animal feed (%) - Human edible energy in animal feed (%) - Gross protein (g / kg of dry matter) - Gross energy (g / kg of dry matter) - Land use (m^2 / kg of dry matter) - Human edible protein in cattle (%) - Human edible energy in cattle (%) - Net production of human edible protein (kg / hectare of UAA) - Net production of human edible energy (10^9 Joule / hectare of UAA) - Production costs (€ / kg of carcass) - Production costs (€ / kg of protein) - Production costs (€0.10^{-6} / J of energy) - Beef production costs (€ / kg of meat carcass produced)	YES	YES	YES	NO
Moughan (2021)	- Land use (HA / T of protein) - Land use (HA / kg of digestible lysine) - Freshwater use (1,000 m^3 / T of protein) - Freshwater use (1,000 m^3 / kg of digestible lysine) - GHG (T of CO_2 eq. / T of protein) - GHG (T of CO_2 eq. / kg of digestible lysine) - GHG (kg CO_2 eq. / 100g of total protein)	NO	YES	YES	YES

	- GHG (kg CO_2 eq. / g of digestible lysine)				
Sabaté et al. (2014)	- Land (m^2), water (m^3), fuel (L), fertilizer (g), pesticide (g), animal waste (kg) / kg of edible protein	NO	YES	YES	NO

Appendix 2

Table 6: Impact per hectare of a production shift away from livestock towards crops-based systems

Transition choice	Gross Margin	GHG emission	Gross protein yield	Available protein yield
Transition to winter wheat, crop with the highest gross margin per HA				
From cattle to winter wheat	+181%	-33%	+1694%	+621%
From dairy to winter wheat	-56%	-70%	+99%	-20%
From sheep to winter wheat	+161%	+11%	+2523%	+954%
Transition to spring oats, crop with the lowest GHG emissions per HA				
From cattle to spring oats	+76%	-63%	+1876%	+1020%
From dairy to spring oats	-72%	-83%	+120%	+25%
From sheep to spring oats	+64%	-39%	+2788%	+1538%
Transition to winter oats, crop with the highest protein yield per HA				
From cattle to winter oats	+87%	-35%	+2378%	+1305%
From dairy to winter oats	-71%	-71%	+175%	+56%
From sheep to winter oats	+73%	+7%	+3522%	+1954%