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RESEARCH ARTICLE

Are Animals Needed for Food Supply, Efficient Resource Use, and Sustainable Cropping Systems? An Argumentation Analysis Regarding Livestock Farming

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Abstract
It has been argued that livestock farming is necessary to feed a growing population, that it enables efficient use of land and biomass that would otherwise be lost from the food system, that it produces manure that is necessary for crop cultivation, and helps improve the sustainability of cropping systems by inclusion of perennial forage crops in otherwise low-diversity crop rotations. In this paper, we analyze these arguments in favor of livestock farming. Through argumentation analysis based on scientific data, we show that the arguments are either invalid or that their validity is limited to certain circumstances. Without taking into consideration any other potential arguments for livestock farming, or arguments against it, we conclude that the arguments analyzed here cannot in isolation provide justification for more than a small proportion of today's livestock farming.

Keywords Livestock farming · Food supply · Argumentation analysis · Resource use

Introduction

Livestock production is a major driver of environmental impacts (Leip et al. 2015; Willett et al. 2019) and is also associated with a number of other sustainability challenges related to working conditions (Hostiou et al. 2020), animal welfare (Rossi and Garner 2014), development of antibiotic resistance (Tang et al. 2017), and emergence of zoonoses (Klous et al. 2016). Many researchers (e.g., Clark et al. 2020; Willett et al. 2019; Röös et al. 2017, 2022) and influential organizations (e.g., IPCC 2019; IPBES 2019; FAO 2019) have called for reductions in livestock production as a crucial strategy to reach environmental targets.

At the same time, there are many valuable services provided by livestock farming. For instance, livestock farming creates jobs and livelihoods, it provides financial security for

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some vulnerable populations, it offers farmers a meaningful life, it supports traditions and cultures, it enhances biodiversity in some places, and so on. Livestock systems however show a wide variety, and the services they bring are highly context specific. Livestock farming varies from intensive land-less poultry production in high-income settings in which the main service is the provisioning of cheap meat to affluent populations, to the keeping of one or a few goats per family in low-income settings providing crucial nutrition, income, financial security and manure for cropping (FAO 2019; FAO et al. 2022).

Moreover, meat and dairy products are highly valued foods in most cultures and have been part of human diets for millennia (Leroy et al. 2023). Animal products are currently central to global food security (FAO et al. 2022), supplying the human population with approximately 18% of the energy and 40% of the protein consumed at global level (FAO 2018). Meat and dairy are especially important as sources of nutrition in food-insecure settings, especially for children that risk life-long chronic physical and mental damage due to stunting (Dror and Allen 2011). Hence, some authors argue that increasing output from animal systems is an important way to provide more nutrition going forward and that investments should be intensified to provide more animal products to a growing population at affordable prices (Ederer and Leroy 2022).

Other authors highlight the role of livestock in upgrading biomass that is not edible by humans into meat and milk by making use of grasslands and by-products from food processing (Karlsson 2022; van Zanten et al. 2018; Thompson et al. 2023). The reasoning here is that without animals these resources would be left 'unused'. Having animals consuming this biomass also helps circulating nutrients back to the soil via manure. Hence animals are also central to crop production, it is argued. Livestock are also claimed to prevent soil degradation and pesticide use associated with low-diversity cropping systems by introduction of grass-legume leys in mixed cropping systems which build soil carbon and help reduce weeds (Leroy et al. 2022). Integrating livestock rearing and cropping in this way is integral to agroecological systems that do not rely on synthetic fertilizers or pesticides (Wezel and Peeters 2014).

It can hence be considered a fact that animal products currently provide crucial nutrients and that the consumption of meat has a long tradition, that livestock can function as biomass 'upgraders' and contribute to sustainable cropping systems. However, the fact that something is a certain way (e.g., animal products currently providing substantial amounts of nutrients), or has been a certain way (e.g., long tradition of meat eating in human history) is not in itself a justification for how something ought to develop. For example, there are a substantial number of human practices that have a long history but are now rejected (e.g., slavery) and that we would not consider justifiable based on the fact that they have been practiced under a long time; all practices have to be judged on their own merits. Following this reasoning, whether or not livestock farming can be justified in the future depends on the costs and benefits it brings, and how its overall assessment stands in comparison to that of available alternatives. While the negative impact of livestock rearing has been thoroughly investigated and documented in the literature, a more detailed analysis of the arguments in favor of livestock farming is missing. Our aim with this paper is to take a closer look at some arguments in favor of livestock farming and assess them using the method of argumentation analysis.

We will focus exclusively on arguments in favor of livestock farming that relate to food production, including converting non-human digestible resources to nutrient dense foods. In other words, we only consider arguments that – directly or indirectly – relate to the capacity of livestock farming within the agricultural sector to contribute to secure and sustainable food production. In particular, we address the following three arguments, each with two sub-arguments:

1. The Nutrition Argument:

   (i) Livestock farming is needed to supply all the different nutrients required for humans to live healthy lives.
   (ii) Livestock farming is needed to supply the amounts of food needed to feed a growing human population.

2. The Resource Use Argument:

   (i) Livestock farming provides a way of producing food from land that is not suitable for growing crops for human consumption.
   (ii) Livestock farming provides a way of producing food from crop residues and agri-food byproducts.

3. The Crop Production Argument:

   (i) Livestock farming contributes to more sustainable cropping systems through inclusion of perennial crops in crop rotations.
   (ii) Livestock farming produces manure that is needed as fertilizer in crop-based food production.

By restricting the discussion to food-producing livestock farming, we omit aspects of animal rearing that relate to sport or companion animals, or animals farmed for production of fur or other non-edible items. Although hunting can be regarded as a food-producing activity, it does not constitute any form of livestock farming, for which reason we do not discuss it here. For the sake of argument, we also assume that there are no ethical impediments to use animals for food production (cf., Regan 1983; Torpman and Röcklinsberg 2021). We also disregard any animal welfare-related aspects of livestock farming that is not directly relevant from the perspective of food production. When crucial for the discussion, we will distinguish between different animal species and farming practices, such as between conventional and organic production, since they sometimes perform differently in various food-producing aspects.

Given the restriction of arguments assessed, it should be noted that this paper does not perform any joint assessment of *all* the positive and negative values that livestock production brings. Hence, it does not allow us to draw any conclusion regarding the overall justifiability of animal farming. However, an analysis of the selected arguments that we conduct in this paper is needed in order for such a conclusion to be drawn.

Methods

The method used in this paper is that of argumentation analysis (e.g., Epstein 2018). In inductive argumentation, such as that concerning livestock farming, argumentation analysis consists of assessing the *strength* of arguments. All arguments aim to support a thesis, i.e., a proposition of some kind. The strength of an argument is its *evidentiary power*, i.e., its capacity to justify the thesis which it aims to support. All the arguments addressed in this paper aim to support the thesis that livestock farming should to be part of future agriculture.

A thesis, and the supporting argument as a whole, can be either *descriptive* or *normative*. A descriptive argument aims to prove or support a claim about how things *are*, an example being the argument that the earth is spherical because it looks so in satellite images. A normative argument aims to prove or support a claim about how things *should be* or *should be done* (cf. Brun and Betz 2016), an example being the argument that people should exercise because it is good for their health. Normative arguments thus attempt to justify some type (or instance) of activity, policy, or individual choice, indicating that they highlight some benefits or positive value of the activity they intend to justify (Hansson and Hirsch Hadorn 2016). Since all arguments scrutinized in this paper attempt to justify continued livestock farming, they are all normative.

There are different ways in which the strength of a normative argument can be analyzed. Here we adopt the view that the strength of an argument is a product of two factors: the argument's *acceptability* and its *relevance* (cf., Feldman 2013). These factors may vary in their degree, for which reason the strength an argument can range from weak to strong. This can be clarified as follows: An argument is acceptable if we have reason to believe that its premises, i.e., the assumptions it makes in support of its thesis, are true (see Epstein 2018). For instance, if there is good scientific evidence that vaccines protect against Covid-19, then an argument that people should take the vaccine based on this premise is acceptable. In order to determine the acceptability of an argument, empirical evidence is needed. However, evidence is sometimes unclear or ambiguous. For this reason, some of the arguments assessed in this paper may be more acceptable than others.

The degree to which an argument is relevant depends mainly on the validity of its premises compared with those of *alternative theses* (see Feldman 2013). For an argument to be sufficiently relevant, its premises must provide sufficient support to establish a conclusion as more probable than rival conclusions. This is important, since an argument could provide support for one thesis just as much as for an alternative thesis, in which case the argument cannot justify its primary thesis. An example is the argument that we should continue to use fossil fuels because it can ensure energy supply. Since energy supply can be ensured using a mix of other energy sources, the energy-supplying capacity of fossil fuels alone cannot justify their use over other energy sources. Thus, even if that argument is acceptable (it is true that fossil fuels can ensure energy supply), its relevance is low, and the argument is therefore weak (cf., Björnsson et al. 2009).

The relevance of any argument for livestock farming also depends on whether there are alternatives to achieving the same outcome that do not involve livestock farming. For instance, if sufficient amounts of food can be supplied without rearing animals in the agricultural sector, then the food-supplying capacity of livestock farming *in itself* is not a sufficiently relevant argument in favor of livestock farming.

Once the acceptability and relevance of an argument have been established to a satisfactory degree, its strength (i.e., the degree to which the argument bears evidentiary power with respect to its thesis) can be assessed. Arguments that fail completely with respect to acceptability or relevance can be dismissed (Björnsson et al. 2009).

It is worth noting that no matter how strong an argument is, its applicability can be more or less general (see, e.g., Epstein 2018). For instance, it might be found that one argument for livestock farming bears evidentiary power only with respect to *a certain type* of livestock farming. There might be important differences between e.g., organic and conventional livestock farming, grazing livestock and feedlot livestock, chicken and beef production, etc. The scope of the argument in this regard must thus be defined in order to determine the *kinds* of livestock farming that can be justified. Moreover, the scope of an argument might be sensitive to geopolitical, socioeconomic, climatic, or other circumstances. As this means, some arguments might be applicable only to certain people (e.g., allergic or undernourished) or in certain regions (e.g., poor countries).

It should also be noted that all arguments for livestock farming could prove to be *individually* weak, but *jointly* strong. In other words, a set of arguments might be capable of supporting a certain thesis over an alternative thesis, although no individual argument in that set is capable of doing so. We return to this issue in the concluding section. First, we must analyze the individual arguments.

The Nutrition Argument

Animal-source foods supply substantial proportions of a number of crucial macro- and micronutrients (FAO 2018; Raiten et al. 2020). This section investigates whether livestock farming is needed to produce all the nutrients needed to secure human health and survival also in the future. More precisely, it investigates whether livestock farming (i) provides important nutrients that cannot be supplied by other means, and whether it (ii) is needed to provide the amounts of food required to feed a growing human population.

Livestock Farming is Needed to Supply All the Different Nutrients Needed for Humans to Live Healthy Lives

The argument that livestock farming is needed to provide important nutrients is clearly acceptable, since through production of meat, fish, milk, eggs, offal, and blood it provides humans with many nutrients. These include macronutrients such as protein and fat, and micronutrients such as vitamins and minerals. In terms of protein, animal products contain all essential amino acids in proportions well-adjusted to human needs (FAO 2013) In terms of micronutrients, animal foods are an important source of e.g., vitamins B2 (riboflavin), B12, and D, as well as the minerals iron, calcium, selenium, and zinc (Raiten et al. 2020; Bakaloudi et al. 2021).

The strength of this argument thus depends on its relevance, which depends in turn on the extent to which livestock farming is *needed* to provide the essential nutrients. If all nutrients could be obtained from non-animal foods, then the fact that they can be obtained from animal foods is no justification for future livestock farming. To assess this, we consider proteins, fats, minerals, and vitamins separately.

Proteins It is indisputable that healthy humans can acquire dietary proteins, in terms of all essential amino acids, through a combination of legumes (e.g., beans, peas, and lentils) and grains (e.g., wheat, oats, rye, and barley). Although bioavailability is lower for plant-based protein sources, this is normally not a nutritional problem (Mariotti and Gardner 2019; Lonnie and Johnstone 2020). There are however people who may be allergic to legumes, and people who are sick, malnourished, or old and therefore need to eat foods with high nutrient density. For these people, meat and dairy products can be important. We return to these exceptions below when discussing the scope of the argument. For now, suffice to say that it is nutritionally possible for healthy adults with access to a variety of foods to replace animal proteins with vegetable proteins (Mariotti and Gardner 2019; Lonnie and Johnstone 2020).

Fats It is known that some fatty acids (e.g., omega-3 fatty acids such as DHA and EPA) can most easily be obtained if the diet contains seafood. However, it is also possible to obtain these fatty acids from algae, either by eating the algae directly or by extracting the fatty acids they contain. The body can also convert the fats in flaxseed and rapeseed oil to DHA and EPA, for which reason animal-source foods are not necessary for adequate fat intake, although for individuals on entirely plant-based diets attention needs to be paid to the ratio of different fatty acids (Burns-Whitmore et al. 2019). If fat supply were to be used as an argument in favor of animal foods, it would thus only apply to seafood, and then only to a very small extent.

Minerals Animal-based foods are an important source of e.g., iron and zinc. These minerals can also be supplied by legumes and whole grains (Röös et al. 2020), but it is not as easy for the body to absorb the non-heme iron in plant-based foods as the iron in meat and fish (Bakaloudi et al. 2021). Therefore, careful planning of vegan diets is necessary (Rogerson 2017). For people with limited access to iron-rich plant foods or fortified products, red meat and offal can be an important source of iron, especially for women (FAO et al. 2022). Calcium can also be difficult to consume in sufficient quantities through a completely plant-based diet. Therefore, dairy substitutes such as oat and soy drinks are commonly fortified with calcium. By consuming such enriched products, it is possible to obtain enough calcium even without dairy products in the diet (Rogerson 2017). However, naturally, this requires that such products are available and affordable.

Vitamins Vitamin D is often limited in vegetarian and vegan diets (Bakaloudi et al. 2021) and is difficult to absorb in sufficient quantities even for those who eat animal-source foods (Cashman et al. 2016). Therefore, dairy products and its substitutes (such as soy and oat drinks) are fortified with vitamin D in some countries, e.g., Sweden. Vitamin B12 cannot be obtained from plant-based foods and hence the argument for animal products in terms of supplying nutrients seems to be of particular relevance in the case of B12. However, those who choose to eat a completely plant-based diet could take B12 in the form of supplements or via fortified foods (if available). Consequently, all essential vitamins can in theory be supplied without animal foods, but supplementation or fortification with B12, and sometimes with other nutrients such as calcium and iron, is necessary (Bakaloudi et al. 2021).

In general, it may be claimed that it is preferable to consume nutrients through ’natural’ animal foods rather than from supplements or fortification foods. Concerns about the environmental impact of supplements are sometimes raised. Data on the magnitude of this impact are largely lacking, but it is likely to be small considering the small volumes used. It is also worth noting that minerals and vitamins are routinely included in animal feed, often in larger quantities per kg of product than for alternative products. For example, to produce one kg of meat or milk, more supplements are used than are needed for fortifying one kg of plant-based alternatives (Röös et al. 2018). It can thus be more efficient to enrich human food directly, rather than indirectly via animal feed.

When it comes to health reasons, there is little evidence that consuming a few nutrients through fortification or supplements in an otherwise well-balanced diet would be worse than to consume nutrients through ‘natural’ animal foods (Dwyer et al. 2015). However, fortification of foods must be carried out with caution, as excessive intake of certain nutrients can be harmful (Meltzer et al. 2003). Even if there were health benefits of consuming B12 (or other nutrients) from animal foods, rather than consuming them through supplements or fortification, relatively large amounts of animal foods are required to provide the daily recommended amount of B12. For adults, the estimated average requirement of B12 is 2.0 micrograms daily (WHO 2005), requiring ingestion of 350 g milk, 100 g cheese, 200 g beef or pork, 700 g chicken, 3 eggs or 100 g fish (or a combination of these) per day. Producing and consuming these amounts of animal foods is associated with costs, for instance in terms of undesired environmental and climate effects. Any potential benefits of consuming B12 through animal-based foods instead of supplements must be weighed against these costs.

It should also be emphasized that there is no guarantee that a diet is healthy just because it contains animal foods. The largest diet-related health challenge in Western countries today is that people eat too *little* fruit, vegetables, legumes, nuts, and whole grains, and too *much* red and processed meat, salt, and sugar (Cena and Calder 2020). There are thus health benefits to a diet with more legumes, whole grains, fruit, and vegetables and less animal-based foods. Replacing some meat with legumes and whole grains would increase intake of fiber and vitamin folate (not found in animal foods), which is currently insufficient in wealthy countries (Röös et al. 2020).

From the above, it can be concluded that the argument that livestock farming is needed to supply the nutrients that people need to live healthy lives, is weak in general. The reason is that it is fully possible from a nutritional perspective to live a healthy life on a diet with no animal products. However, this would require supplementation of some nutrients, knowledge of how to compose a diet that meets all nutrient requirements, and access to such foods. In many low-income settings, there is a lack of diversity of foods, and diets are lacking many essential nutrients (FAO et al. 2022). A certain proportion of the human population is suffering from micronutrient deficiency, which is especially serious for children (Dror and Allen 2011). For people living under such conditions, a small portion of animal foods can contribute substantially to healthy outcomes. Consequently, the argument under scrutiny bears relevance *for these people*. However, this is because alternatives are lacking in those settings, not because only animal foods can supply these nutrients. Note also that the argument has little relevance for populations in high-income settings. Although meeting one's nutritional needs with some animal products in the diet is easier for people used to eating an omnivore diet, it is possible for healthy people with no special needs – with the proper education and support – to consume all needed nutrients via a plant-based diet in these settings where a wide variety of foods is available.

Livestock Farming is Needed to Supply Sufficient Amounts of food for a Growing Human Population

To determine the strength of the argument that livestock farming is needed to produce the *amounts* of food needed to feed a growing human population, we first investigate the degree to which livestock farming supplies foods to the global food system currently – i.e., to what degree livestock farming is a *net producer* of food.

If the nutrients in the crops produced currently globally are divided upon the global population, these contain the equivalent of approximately 5810 kcal energy, 143 g protein, and 152 g fat per person per day (Ritchie et al. 2018). Some of these crops are used as seeds or for bioenergy production and other industrial uses, leaving 4195 kcal, 114 g protein, and 94 g fat per person per day. A large part of these crops is used for animal feed (1514 kcal, 72 g protein, and 18 g fat). The animal products produced from this feed contain lower amounts of energy and protein than were in the feed (572 kcal and 37 g of protein), but a higher amount of fat (43 g). In total, therefore, global production of animal foods involves a net loss of calories and protein, but a net gain of fat. In effect, an additional four billion people could be fed energy-wise on the crops currently used as animal feed and the supply of protein could be doubled (Cassidy et al. 2013).

This competition between livestock and humans for the same resources for feed and food (called food-feed competition; van Zanten et al. 2018; Wilkinson & Lee 2017) means that current livestock farming is a net sink of energy and protein. Hence, the argument that livestock farming is needed to produce enough food is *not in general* acceptable based on how livestock farming is performed today. However, livestock farming produces more fat than it consumes. To determine the relevance of the latter, we therefore need to consider whether more fat is needed to feed a growing global population and whether the net positive amount of fat that is produced through livestock farming can be supplied in other ways.

The 2008 joint FAO and WHO expert consultation advised that fats should contribute to 20–35% of total energy intake in humans (FAO 2010). Based on this requirement, Bajželj et al. (2021) estimated that there is a need for an additional 45 Mt of dietary fat per year for the current global population to reach these recommended levels, or 88–139 Mt to supply the projected population in 2050 with adequate amounts of fat. Considerable amounts of vegetable fat are currently produced for purposes other than food production, including substantial amounts of palm and soy oil that are used e.g., for bioenergy, cosmetics, and hygiene products (Bajželj et al. 2021). This oil could be used for food products instead, in which case the net positive amounts of fat that livestock farming produces today would not be needed. Instead, humans could get all the dietary fats they need from plant-based sources (Bajželj et al. 2021).

However, that would reduce the amount of fat available for other purposes. To remedy any subsequent shortage of fat in this respect, there is potential to increase current production of plant-based fats, although several sustainability concerns then need to be carefully considered (Bajželj et al. 2021). For example, increased production of palm and soy oils risks leading to deforestation with negative social and ecological impacts, rapeseed (the most common oilseed crop in Europe) cannot be grown too often in crop rotations due to pest and disease susceptibility, and olive oil requires large areas of land (Bajželj et al. 2021). On the other hand, some emerging technologies could offer sustainable alternative ways to produce fat, including e.g., fats from microorganisms or insects (Kouřimská and Adámková 2016).

Given current uncertainties on these matters, it can be concluded from the above that *some* livestock farming may be justified in terms of food supply when it comes to fat, assuming that sufficient fat cannot be supplied sustainably from current or novel plant-based or microbial sources. More research is needed to determine the extent to which certain livestock systems (if any) could fill this role of fat provider while not reducing the amount of energy and protein available. In any case, the wider applicability of the argument is limited.

The Resource Use Argument

While livestock farming may not be necessary for production of the nutrients and amounts of food required to feed a growing human population, it has been argued that livestock farming provides an efficient way of utilizing *certain resources* for food production (van Zanten et al. 2019; Karlsson and Röös 2019). For instance, some agricultural land that is not suitable for growing crops at a quality level making them suitable for human consumption could be used to feed animals. The same holds for some by-products and wastes that are not suitable for human consumption. In this section, we examine this resource use argument in terms of two sub-arguments: (i) livestock farming allows for efficient use of land for food production, and (ii) livestock farming allows for efficient use of residues for food production.

Livestock Farming Provides a Way of Producing Food from Land that is Not Suitable for Crops for Human Consumption

To establish the acceptability of the argument that livestock farming provides an efficient way of producing food from land not suitable for crops for human consumption, we first need to distinguish between land that is only suitable for grazing and land that is only suitable for cropping, a distinction that is not straight-forward. Some of the land currently used for grazing could technically be cultivated, but this is not done for economic or practical reasons, while some land is more or less impossible to cultivate because it is temporarily flooded, too rocky, or etc. Some land might be cultivated but with detrimental effects for soils, e.g., cultivation of annual crops on slopes can lead to soil erosion (Shanshan et al. 2018). Globally, it is estimated that two-thirds of the world's grassland areas currently used for grazing animals could not be converted to cropland (Mottet et al. 2017). Therefore, we must accept that the argument at issue is acceptable with respect to a substantial amount of global agricultural land, since the only way to use a large portion of this land for food production (at least by technologies currently deployed at scale) is by keeping grazing animals on it.

Turning to land that could be cropped, a typical argument is that the cropland in some regions, e.g., in northern Scandinavia, is not suitable for growing food for humans, but can be used for producing animal feed, primarily perennial forage crops such as grass-clover leys. It is true that high-latitude regions have less favorable conditions for growing (some types of) crops for human consumption than medium- and low-latitude regions. This depends partly on climate and soil type, but also on aspects that are not inherent to the land per se, such as long distances to cities (where the majority of consumers live), high transportation costs, or production limitations due to lack of infrastructure such as processing facilities (Jordbruksverket 2012). In addition, traditions often influence what is produced, certain types of production might fit well in practice with other off-farm activities pursued by the farmer, and investments might already have been made in buildings and machinery for livestock farming. Moreover, for some crops (e.g., legumes) there is high variability in yield between years and, although on average over the years these crops could supply more food than livestock production. Livestock farming can therefore provide a more stable income, even if the economic outcome from livestock farming is still sensitive to the price of meat and milk and the cost of inputs such as feed, fuels, and fertilizers. Quality of the harvested crops is also an issue, e.g., land in some regions might be suitable for cropping of feed grade grains but not food grade (more on this in Livestock Farming Provides a Way of Producing Food from Crop Residues and Agri-Food Byproducts section).

Although much agricultural land in high-latitude regions is currently used for forage cultivation, the acceptability of the resource use argument (when applied to land use for forage cultivation) depends on whether other food production systems would be equally (or more) efficient in these areas. Based on currently used production methods, it is possible in some of these areas to grow crops for human consumption. For example, northern Sweden has a long tradition of growing potatoes and berries and there are ongoing investments in increasing horticulture production and using land areas for cereal production for food.[1] Hence, livestock farming is currently common in these areas mainly for economic reasons, not for the reason that it is biophysically impossible to grow food for human consumption on the land.

A crucial question to determine the strength of the argument is, then, whether livestock farming or cropping provides food most efficiently in these regions. To assess this, let us consider an example in which one hectare of agricultural land in a region of Sweden with poor growing conditions is used for grass-based milk and meat production (see Appendix for data and calculations). This would produce about 3.5 million kcal and 190 kg of protein in meat and milk per hectare, assuming grass biomass production of 7 tons of dry matter per hectare, and a milk yield of 6 tons per cow and year (Cederberg et al. 2018; Jordbruksverket 2021). If grain were to be grown for human consumption on the same hectare of land, a grain yield of 2700 kg per hectare would be required to produce the same amount of protein and a grain yield of 1100 kg per hectare would be required to produce the same amount of energy. In practice, grain yield in northern Sweden is 2500–3000 kg per hectare depending on the crop, which suggests that grain cultivation, despite low yield, can be a more land efficient way of producing energy than meat and milk production in these areas.

However, cereal grain does not contain all essential amino acids in proportions that corresponds to human needs, while milk and meat do (FAO 2013). To supply a more complete protein profile without providing excess energy, protein crops (i.e., grain legumes) would need to be grown in addition to cereal crops. It is difficult to grow beans in northern Sweden because they require a long growing season to ripen, but other protein crops such as peas, lupin, and vetches can be grown. To produce as much complete protein as from the corresponding animal food production per hectare, a grain yield of about 3000 kg per hectare and a pea yield of about 1100 kg per hectare would be needed (meaning that about half of the hectare would be cropped with grain and the rest with peas). Grain yields at this level are possible in northern Sweden, but pea yields are more questionable (Jordbruksverket 2021; G. Carlsson, Prof in Cropping System Ecology, SLU, pers. comm. 2022).

Hence, there are areas where feed cultivation for milk production produces more food than cultivation of edible crops on the same area, so an argument can be made in favor of *this type* of livestock farming *in these areas*. A similar analysis would need to be made for other areas for which livestock production is claimed to be justifiable because only animal feed can be grown in the area. Note that this reasoning *does not* apply to pure beef or lamb production in the Nordic region considered here, as it produces substantially less energy and protein than milk production, or to production where the animals eat grain and protein feed (e.g., pig, chicken, egg, and intensive milk production), as such crops would provide food more efficiently if eaten directly by humans.

We can conclude that the arguments for continued feed cultivation on cropland that is unsuitable for crop production for human consumption, and for continued livestock grazing in areas which cannot be used more efficiently in other ways, are acceptable and relevant for justifying livestock farming given that they provide the only way to use these areas for food production. However, the relevance of both these arguments can still be questioned, since they both presuppose that all currently used agricultural land should be used for *food production*. However, some of this land might be better used for other (i.e., non-food

[1] See, e.g., http://www.ojebynagropark.se/.

related) purposes. For instance, some land might be suitable as a natural carbon sink, as a nature reserve, for forestry, for rewilding, for mining, for wind farms, for solar panels, etc. Livestock farming is compatible *to some extent* with other such ways of using land. But, although there are ways to have multifunctional systems, there will always be competition for land. It should thus be noted that compatibility of this kind is at best partial, since no same area can be fully used for both rearing animals and solar panels, to give an example. Moreover, certain alternative usages are completely incompatible with land use for livestock farming, such as land use for wild ecosystems. Hence, in order to determine the relevance of the land use argument, it is necessary to look beyond mere food production systems. Here we cannot make the comparisons needed to settle this issue, which is also highly context-specific, but merely point to the need for such comparisons before the strength of the argument can be determined. In any case, our previous lines of reasoning suggest that the argument is applicable only to a limited portion of the land currently used for livestock farming.

Livestock Farming Provides a Way of Producing Food from Crop Residues and Agri-Food Byproducts

Let us now consider the argument that livestock farming is needed to make use of residues and byproducts from the agricultural sector that would otherwise remain unutilized. These include residues from the food and energy industries, such as bran, rapeseed cake (residues from rapeseed oil production), molasses, and beet fiber (from sugar production), brewery waste (from beer production), distiller's grain (from ethanol production), various other waste streams from the food industry, and crop residues such as straw.

The concept of restricting livestock farming to available residues and byproducts, and in that way avoiding food-feed competition, is well documented in the literature under various labels, including "default livestock" (Fairlie et al. 2010), "ecological leftovers" (Garnett 2009; Röös et al. 2018; 2017), "non-food competing livestock" (Muller et al. 2017), "low opportunity cost-feed" (van Hal et al. 2019), and "circular food systems" (van Zanten et al. 2019). Multiple modeling studies have been carried out to estimate the amount of animal protein that could be produced, globally and in different world regions, if animal production were to be limited to using residues and by-products as feed. The results indicate that a substantial amount of the global protein requirement could come from livestock farming based on feeding available residues and byproducts (van Zanten et al. 2018). However, much of this protein would derive from animals raised on food waste, which carries the risk of spreading infectious diseases (Dame-Korevaar et al. 2021).

This suggests that the use of residues argument is acceptable for a certain scope of livestock farming, since a substantial amount of food can be obtained from these resources by using them as livestock feed. The relevance of the argument seems to hinge on whether livestock farming is the best way of using these residues for food production. We thus need to look at whether there are ways other than livestock farming of returning residues and byproducts currently used as animal feed to the food system.

In fact, several of the byproducts currently used as animal feed could be used as human food instead. For example, distiller's grain can be used in bakery products (Martins et al. 2017), while the soy meal that remains when oil is pressed out of the whole soy bean is already processed into soy products for human consumption (Karlsson Potter et al. 2020). Humans could also eat (more) bran to increase their fiber intake, which is commonly low in Western diets (Barber et al. 2020) (although increased content of contaminants in whole grains compared to refined grains can be a concern; Thielecke and Nugent 2013). It is worth noting that, in a sense, even grass and leaves *can* be eaten by humans, as it is possible to extract proteins from them, which could produce large amounts of protein per hectare (McDougall 1980; Solati et al. 2017). Leaf protein concentrate has a high-quality amino acid composition and could be processed into different types of food. It is generally more resource-efficient to utilize residues by eating them directly (after processing) than by letting them first pass through an animal, where large proportions of the energy and nutrients are lost in the animal's metabolism. However, the need for processing energy must of course be considered.

In any case, it is difficult to define unambiguously whether a certain type of biomass or residue can be used as human food, since what humans consider as food is largely determined by factors such as habits, traditions, and taste. This applies also to grains, since e.g., for wheat to be classified as food-grade, it must meet high requirements in terms of protein content to enable bread-making in industrial processes. If the grain does not meet those requirements, it is classified and used as animal feed, although it could be used as human food, such as e.g. muesli. A study on the Swedish cereal market showed that a large proportion of the grain used as animal feed today is actually of food quality (Tillgren 2021).

It is still the case that *some* byproducts may be difficult or even impossible to process into products that are palatable for humans. Therefore, the residues use argument is acceptable and relevant with regard to *these* particular byproducts. Note that, just as in the case of land use discussed in the previous sub-section, it must first be determined whether there are *other* ways of utilizing by-products and residues that would create just as much value. Some residue products are already used for bioenergy production or returned to the soil, contributing carbon and nutrients to cropping systems (see more on this in the next section).

Moreover, the extent to which humans really *need* the extra amounts of food that livestock can produce by converting inedible residues into food for human consumption must be determined. If we used more of the land and available crops to produce human food directly (see Livestock Farming is Needed to Supply Sufficient Amounts of Food for a Growing Human Population section) and wasted less food, in theory there would be enough food to feed the global population. However, it has been shown that using residues as livestock feed would reduce the need for cropland compared with a completely vegan diet (Röös et al. 2017). In a similar vein, van Kernebeek et al. (2016) showed that for the Netherlands, land is most efficiently used if 12% of the dietary protein comes from animal products, especially milk.

To recap, to some extent humans could eat more of the residues and byproducts from agrifood systems. However, some residues cannot be eaten by humans or used for non-food related purposes, and the argument that livestock farming enables more efficient use of resources is thus valid for *these* residues and under the assumption that alternative usages (e.g., for bioenergy or soil amendments) are less valuable. In any case, the quantity of animals reared in current livestock farming is not needed to utilize these resources, as a large part of today's animal feed either does not consist of residual products that humans cannot eat, or does not come from land that could not potentially be used for cropping or for other non-food purposes (Mottet et al. 2017). As is the case with land use, the current situation regarding re-use of residues is highly dependent on people's preferences, technological developments, and political feasibility, which might change in the future.

The Crop Production Argument

Agricultural food production systems are complex. Even if the meat, milk, and eggs produced in livestock farming are not necessary for feeding a growing human population in terms of nutrients or amounts (as argued in The Nutrition Argument section), and even if the scale of today's livestock farming is not needed to make efficient use of lands and/or agri-byproducts (as argued in The Resource Use Argument section), it is sometimes claimed that livestock farming is necessary for sustainable cropping because (i) it introduces perennial forage crops (e.g., grass-clover leys) into low-diversity crop rotations, and (ii) it provides manure that is needed as fertilizer. Both these practices are part of mixed crop-livestock farming systems central to agroecology (Clark 2004; Wezel 2017). In this section, we examine these crop production arguments.

Livestock Farming Contributes to More Sustainable Cropping Systems by Inclusion of Perennial Crops in Crop Rotations

Depletion of agricultural soils is a serious problem globally (Kopittke et al. 2019). One of the most important factors for a fertile soil is its content of organic matter (Johnston et al. 2009). Soil organic matter consists of degraded plant and animal parts and various types of microorganisms, with around 50% consisting of carbon. Soil organic matter helps to give the soil a good structure and water-holding capacity, and functions as a nutrient reservoir for microorganisms and plants. Large amounts of soil organic matter have been lost from the world's agricultural soils in the past hundred years (Kopittke et al. 2017), which has seriously impaired soil fertility in some regions. Globally, large losses of soil carbon occur via erosion. Soil organic matter is also generally lost in annual cropping (involving crops such as cereals, legumes, and oilseed crops), as smaller amounts of crop residues and roots are added to the soil in comparison with perennial crops (e.g., grass, alfalfa, and clover) that cover the soil throughout the year (Kopittke et al. 2017).

One way to preserve and build soil organic matter is to introduce perennial crops (e.g., grass-clover leys) into low-diversity cropping systems (Martin et al. 2020; Zhou et al. 2019). Introducing perennial crops into crop rotations is also a way of handling weeds without using herbicides, since mowing the field repeatedly during the season kill perennial weeds (such as thistle). In colder climates, another advantage of perennial leys in crop rotations is that the soil is not left bare during the winter, which reduces the risk of nutrient and soil carbon losses. Legume crops in leys also contribute to fixing nitrogen from the air, reducing the need for artificial nitrogen fertilizer for subsequent crops. To alternate between leys and annual crops is a basic principle of agroecological farming (Wezel 2017). In organic farming, for example, the use of perennial leys is critical because synthetic fertilizers and synthetically produced herbicides are not permitted (e.g., EU 2018).

However, in most of current conventional agricultural systems, perennial forage crops are not part of cropping systems. Instead, annual crops are commonly grown in low diversity crop rotations, where nitrogen is supplied by synthetic fertilizers, and where weeds are handled with herbicides. In a totally plant-based food system based on conventional cropping, there would be no need for perennial leys. Therefore, one could argue that livestock rearing of grass-eating animals (e.g., cattle, sheep, horses) is justified because it leads to introduction of perennial crops in monoculture cropping systems and thereby supports soil fertility.

This argument is clearly acceptable given that ruminant animals often eat perennial forage crops. However, in many regions worldwide, grass-eating animals such as ruminants are currently fed with maize and other crops that are *not* perennials, and hence do not deliver the mentioned benefits. Therefore, the argument is not acceptable in such cases. In addition, in situations where *the purpose* of introducing perennial crops into cropping systems is to supply nitrogen to annual crops and handle weeds (as in organic cropping systems) as opposed to the main purpose being to grow feed for ruminants, this argument would also fail to be acceptable as it is not the livestock that lead to the introduction of the perennial crops in those cases. In such cases, an argument for livestock as users of this biomass resource can be made, but that is *another* argument (scrutinized in The Resource Use Argument section).

The relevance of the argument at hand depends on whether introduction of perennial forage crops into cropping systems is really needed for maintaining or enhancing soil fertility, including maintaining or increasing soil organic matter content, or whether this could be done in alternative ways. Some argue that soil organic matter content can be increased sufficiently through high yields, intermediate crops, and reduced tillage – so-called 'conservation agriculture'. However, the evidence that conservation agriculture can deliver soil carbon sequestration is not conclusive (Sun et al. 2020), and conservation agriculture is often dependent on herbicides to manage perennial weeds (Hunt et al. 2010), a practice which could be deemed unsustainable. In addition, perennial leys provide many other benefits to cropping systems such as providing biological control of pests and habitat provisioning for biodiversity conservation (Martin et al. 2020). Therefore, others claim that perennial crops such as grass-legume leys are indispensable for sustainable cropping systems.

If we accept that perennial crops are a prerequisite for sustainable cropping systems, the question is whether livestock farming is needed to enable inclusion of these in crop rotations. To resolve this, we need to establish whether it is possible to have perennial grass-legume crops in cropping systems without involving animals.

In principle, it is of course possible to grow perennial grass-legume crops in crop rotations without having animals on the farm. Thus, livestock farming is not in principle necessary for the cultivation of perennial forage crops. However, most farms that grow perennial forage crops keep animals, as there are seldom alternative sales outlets for the grassland biomass.

There are however alternative uses for the grass and legume biomass from perennial leys. One is so-called *green manure*, where grass biomass is chopped into small pieces and either left in the field, composted, or made into silage to be used as a fertilizer at a later time (Råberg et al. 2018; Kumar et al. 2020). Use of green manure can be challenging, however, partly because it does not provide the farmer with any financial income from the land used for green manuring (although fertilizer cost is reduced), and partly because it can lead to large nutrient losses as it can be difficult to synchronize the nutrient supply with crop needs. However, green manuring is being used in many places globally to improve soil fertility and reduce the need for external nitrogen inputs (Meena et al. 2018). Practical trials and research are underway to improve the use of green manure (Ward et al. 2023).

Another alternative use of grass biomass is to digest the biomass for biogas production. In addition to the gas, this process also gives rise to a digestate that can be used as fertilizer. However, digestion of grass biomass is unusual. In an interesting initiative in Finland, grass biomass from three animal-free organic farms is digested in a biogas plant and the biogas is used partly for production of electricity and heat, but is also upgraded and sold as vehicle fuel, while the digestate is used as fertilizer on the three farms (Koppelmäki et al. 2019). Hence, there *are* alternative uses for the biomass from perennial crops grown in crop rotations, so strictly speaking livestock farming is not needed for sustainable cropping systems that include grass-legume leys. However, livestock farming is sometimes the only profitable or practical option for using ley biomass, due to the cost involved in investing in a biogas plant, low energy prices, lack of infrastructure and supportive energy policies, meaning that the crop production argument must be considered acceptable in those cases.

Note, however, that for the argument to be relevant, the perennial crops need to be grown in rotation with food crops, i.e., integrated into cropping systems on cropland and not grown continuously year after year on the same field. Only then can the benefits of these crops contribute to the cropping system. In the plain region of Sweden, for example, annual crops are usually grown without inclusion of leys in the rotation, while leys dominate the rotation in less fertile forested areas (Karlsson 2022). Only 12% of the leys in Sweden are an integral part of crop rotations, typically with one to three years of ley in a seven-year crop rotation, while 46% of Swedish leys are grown in systems with continuous leys year after year. The argument that livestock farming is needed for enhancing annual cropping systems is only applicable if the perennial crops are part of crop rotations in which annual crops are grown. Only then can grass cultivation be justified solely for animal agriculture based on this argument.

It is also important to emphasize that the argument applies only to a limited number of animal species. It is first and foremost applicable to ruminants and horses, as these animal species eat the grass and forage legumes (e.g., clover) produced in mixed leys. To some extent, the argument applies also to pigs, which can assimilate a certain amount of grass in their diet (Friman et al. 2021). Organic pig and poultry production regulations require these animals to have access to roughage, which means that organic pig and poultry production to some extent also contributes to cultivation of grass-legume leys. In biorefineries, the protein fraction can be extracted from grass biomass and used as feed for chickens and pigs (and humans), thus replacing imported soy-based feed (Ravindran et al. 2021). However, large quantities of grain would still be needed in the diet of these monogastric animal species, and any cropping system for pig and poultry feed would thus still be dominated by cultivation of annual crops, not perennial forage crops. Livestock farming systems (such as organic production) that involve feeding ruminants more roughage and less grain and other concentrates provide more value from this perspective, as they contribute to more grass-legume leys (Gaudare et al. 2020).

In summary, the argument that livestock farming is needed for its contribution to inclusion of perennial forage crops in cropping systems is valid only for grass-eating species such as ruminants and horses, and only given that the perennial forage crops are integrated with cultivation of annual crops in mixed cropping systems. It is worth noting that while a substantial proportion (56%) of the world's ruminant animals are currently kept in mixed systems (i.e. integrating cropping and livestock), another substantial proportion is kept in grazing or intensive systems, hence not contributing to the sustainability of cropping systems (Herrero et al. 2013).

Livestock Farming Produces Manure that is Needed as Fertilizer in Crop Production

All forms of livestock farming give rise to manure, which is a valuable fertilizer. A common argument for livestock farming is that the manure it supplies is needed to produce plant-based foods, i.e., that with no or fewer animals there would not be enough fertilizer for cropping. This section scrutinizes this argument.

To assess whether the argument is acceptable, we need to determine whether it is true that livestock farming is a net producer of fertilizer through production of manure. The most important nutrients for most agricultural crop production are nitrogen, phosphorus and potassium, which we shall consider separately for the sake of clarity.

Nitrogen derives originally from the atmosphere, which contains 78% nitrogen gas. There are currently two ways by which atmospheric nitrogen can be taken out of the air to be made available to plants: either through growing legumes (with help from bacteria in the soil) or by making artificial fertilizers industrially. Interestingly, neither of these methods involves animals. Only for animals that eat legume forage (e.g., cattle, sheep, horses) can the manure contain more nitrogen than is needed to produce the feed itself. For animals that eat mainly cereals (e.g., pigs and chickens), there are no plant nutrients in the manure that can be used for anything else than producing feed for the animals themselves, for the simple reason that the feed crops for these animals (from which the nutrients in the manure comes) need this amount of nitrogen to grow. It is therefore important to distinguish between animals that eat substantial amounts of legumes (which do not need to be fertilized with nitrogen) and animals that eat other crops (e.g., grass, cereals) that need to be fertilized with nitrogen. Hence, the fertilizer argument is only acceptable concerning nitrogen for such systems, e.g., ruminant systems in which the animals are fed forage containing considerable amounts of legumes (e.g., clover or alfalfa).

Phosphorus derives originally from mining and therefore needs to be added from outside the farm. Substantial amounts of phosphorus are typically added as a supplement, with minerals and vitamins, to the mineral feed used for animals (WWF 2021), and part of this phosphorus ends up in the manure. Manure is currently an important source of phosphorus, especially in organic farming, but phosphorus can be added to the soil directly instead of to animal feed. Most importantly, phosphorus is not *produced* in the animal and the manure functions mainly as a 'carrier'. For this reason, the argument that animals are needed for supplying cropping systems with phosphorus is not acceptable.

Potassium derives originally from mining, atmospheric deposition or, on some soils, weathering (Mikkelsen and Roberts 2021). As with nitrogen and phosphorus, potassium in the manure is not *created* in the animal but supplied in the feed eaten by the animal.

Overall, therefore, livestock farming does not contribute to net production of the main plant nutrients found in manure, except for nitrogen in manure from legume-consuming animals (i.e., mainly ruminants and horses). The nutrients in the manure come from plants, and livestock *circulate* them within the livestock system *itself*. In addition, it is also worth mentioning that manure that is deposited on grasslands from grazing animals cannot be applied to crops.

An important aspect to note in relation to this is that even if livestock farming does not *produce* any nutrients, it could be argued to be important for its capacity to *store* or *transfer* nutrients. Indeed, when animals eat legumes, they absorb the nutrients which then end up in a more concentrated form in the manure, a form that is also more accessible to plants. The manure can be stored for later use, facilitating timing with crop needs, or transported to a different farm. A charitable interpretation of the situation is therefore that the manure fertilizer argument is acceptable in cases where animals are crucial for storing, moving, and concentrating nutrients in time and space – especially when other means for doing so are lacking or are more expensive or energy demanding.

Whether the argument is relevant depends on whether there are alternatives to storing and transporting the nutrients in biomass for use as fertilizer in cropping systems. As discussed in "Livestock Farming Contributes to More Sustainable Cropping Systems by Inclusion of Perennial Crops in Crop Rotations" section, biodigesting, composting, or ensiling biomass is an alternative way of producing a fertilizer that can be stored, moved, and transported (Råberg et al. 2018; Kumar et al. 2020). In conventional cropping systems, nutrients are supplied to soils using artificial fertilizers, so in this case there are clearly alternatives. However, artificial nitrogen fertilizers are energy-demanding to produce, contribute substantially to climate change, easy to overuse, and do not contain carbon which is important for accumulation of soil organic matter and soil fertility (see Livestock Farming Contributes to More Sustainable Cropping Systems by Inclusion of Perennial Crops in Crop Rotations section). Hence there are reasons for using other types of fertilizers rather than artificial fertilizers. Importantly, there is huge potential to recycle nutrients from society, e.g., in human urine and feces from sewage treatment plants and in food waste (Akram et al. 2019).

In addition, there are some important values of manure that are at risk of being lost if the manure is replaced with composted, ensiled, or digested biomass. For instance, different fertilizers affect the presence of different soil organisms (e.g., earthworms, fungi, nematodes, bacteria) in different ways (Viketoft et al. 2021). Soil organisms are important for several ecosystem functions, such as breaking down plant residues. A factor in favor of animal manure would be that it possesses some important and unique qualities, but there are few indications that this is the case. More research is needed to determine the value of manure in this respect compared with its alternatives.

From the above, it can be concluded that livestock farming in general is a net producer of neither phosphorus, nitrogen, nor potassium fertilizer. Consequently, the argument is for most livestock farming systems not acceptable. The argument that animal farming produces manure that is needed as fertilizer for crop production is only acceptable for nitrogen under the assumption that the animals eat considerable amounts of legume feed crops. In terms of relevance, there are alternative ways of fertilizing cropping systems, e.g., using (sustainably produced) synthetic fertilizers, recycling nutrients from society or supplying the nutrients in the plants (that the animals would otherwise eat) directly to the soil as green manure. Hence this argument for livestock farming only applies in situations where such alternative options are not feasible.

Conclusions

In this paper, we have scrutinized three major arguments (with two sub-arguments each) in favor of livestock farming: (1) the nutrition argument; (2) the resource use argument; and (3) the crop production argument. Our analysis shows that all these arguments have limited acceptability and relevance for livestock farming in general, and that their respective scope of applicability is narrow.

To summarize, the arguments were shown to bear weight only in cases where livestock farming is needed to:

1(i) produce nutrients for people who cannot acquire them through a plant-based diet and/or supplements, which includes some allergic, old, sick, or malnourished people and people lacking access to alternatives to animal products;
1(Ii) Potentially secure enough fat for the growing global population;
2(i) make use of land for food production, mainly of areas where crops for human consumption cannot be grown and where other types of usages (e.g., for energy production, rewilding, or carbon sinks) are less valuable;
2(ii) make use of residues that humans cannot eat directly, and where the use of these resources for other purposes (e.g., production of energy, soil amendment, or fertilizer) is less valuable;
3(i) drive the inclusion of perennial forage crops in crop rotations, which is important for sustainable crop production. This argument is limited to grass-eating species such as ruminants and horses and only valid if the perennial feed crops are integrated with cultivation of annual crops in mixed cropping systems;
3(ii) store or transport plant nutrients, particularly nitrogen, via manure to cropping systems. This requires that the animals eat legume feed crops and that good alternative ways of applying the nutrients in the biomass that animals eat are lacking.

How much of today's livestock farming that meets these criteria is unclear, although there have been some attempts to quantify the potential to produce animal protein from grassland and residues (2i and 2ii). For instance, van Zanten et al. (2018) compiled results from several studies and found that between 9 and 23 g of animal protein per capita and day could be supplied from such resources, which is considerably less than current consumption levels in high-income settings.

Our aim in this paper has been to identify and scrutinize the conditions under which the considered arguments can justify future livestock farming. There are certainly *other* (i.e., non-food related) arguments in favor of livestock farming, and other arguments *against* livestock farming, that should be taken into account. In this paper, we put these to one side for the sake of stringency, and simply note that they must be considered before drawing final conclusions regarding the overall justifiability of livestock farming, its scale and type. It is also worth repeating that we assumed that there are no ethically principled restrictions to the use of animals in food production. If such restrictions apply, they will further limit the moral justifiability of future livestock farming.

Appendix: Data Used for Comparing Food Production from Low Intensity Grass-Based Dairy Production and Cereal and Legume Production from One Hectare of Land

Table 1 Calculation of the potential production of energy and protein from one hectare of land using grass-fed dairy production

	Dairy cows	Offspring 0–1 years	Offspring 1–2 years	
Number of animals per hectare[1]	0.76	0.76	0.76	
Slaughtering weight, kg carcass weight	280		298	
Number of animals slaughtered per year[2]	0.23	0	0.53	
Grass feed consumed per year per animal, kg[3]	5200	1800	2200	
Grass feed consumed in total[4]	3952	1368	1672	
Grass yield, kg per hectare	7000	7000	7000	
Land used for feed production, hectare[5]	0.6	0.2	0.2	
Milk yield, kg per cow and year[6]	6000			
Meat produced per year, kg bonefree[7]	45	0	111	
Milk produced per year, kg[8]	4560			
Energy and protein produced in meat and milk[9]:				Sum:
Energy, kcal	3,285,845	0	233,048	3.5 M
Protein, kg	164	0	22	190

1 One hectare of land can produce grass for 0.76 dairy cows and 2 × 0.76 offsprings

2 Assuming a recruitment rate of 30%, i.e. 30% of dairy cows are slaughtered each year and replaced by heifers going into dairy production

3 From Cederberg et al. (2009)

4 Calculated as no of animals * grass feed consumed

5 Calculated as total feed used / grass yield

6 From Cederberg et al. (2018)

7 Calculated as no of animals slaughtered per year * slaughtering weight * 70% (70% being amount of bonefree meat per kg carcass weight)

8 Calculated as no of dairy cows * milk yield

9 Calculated with nutritional values in Appendix Table 2

Table 2 Energy and protein content and protein digestibility of foods (Sonesson et al. 2017) included in the calculations

	Energy, kcal	Protein, kg	Protein digestibility
Beef meat	2100	0.2	1
Milk	700	0.034	1
Cereals	3500	0.08	0.96
Legumes	3170	0.215	0.78

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Declarations

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