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Can 100% Pasture-Based Livestock Farming Produce Enough Ruminant Meat to Meet the Current Consumption Demand in the UK?

Aiming Qi [1,*], Louise Whatford [2], Sophie Payne-Gifford [1], Richard Cooke [1], Steven Van Winden [2], Barbara Häsler [2] and David Barling [1]

[1] Centre for Agriculture, Food and Environmental Management Research, School of Life and Medical Sciences, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK; s.payne-gifford@herts.ac.uk (S.P.-G.); r.cooke2@herts.ac.uk (R.C.); d.barling@herts.ac.uk (D.B.)

[2] Veterinary Epidemiology, Economics and Public Health Group, Department of Pathobiology and Population Sciences, Royal Veterinary College, Hawkshead Lane, North Mymms, Hatfield AL9 7TA, UK; lwhatford@rvc.ac.uk (L.W.); svwinden@rvc.ac.uk (S.V.W.); bhaesler@rvc.ac.uk (B.H.)

* Correspondence: a.qi@herts.ac.uk

Abstract: Grassland is grouped into temporary, permanent, and rough grazing types in the United Kingdom (UK), making up more than 60% of the national agricultural land area. It provides avenues for grazed fodder or ensiled forage contributing a large proportion of the diets consumed by cattle and sheep. The official agricultural census data in 2011 to 2020 showed that, on average, UK cattle and sheep farming can produce meat to satisfy 83.3 and 100.8% of domestic cattle beef and sheep meat consumption levels, respectively. Out of the large agricultural census datasets, we used the populations of cattle and sheep, as well as the UK definition of a standard livestock unit (SLU), to normalise the respective herd populations into a total standard livestock unit (TSLU). We then used the annual domestic meat production in dressed carcass weight to calculate cattle and sheep meat productivity per SLU. Using the potential herbal dry matter yields per year and areas of the different grassland types across the UK, the potential total available pasture feed was calculated. This potential production of herbal biomass was translated into the potential carrying capacity expressed in a TSLU. This total potential carrying capacity was partitioned into cattle and sheep sectors so that the routes of pasture-based-only options with which to produce ruminant meat to meet the current UK domestic consumption demands were assessed. The estimated mean potential annual pasture forage feed in 2011–2020 was approximately 82.0 million (M) metric tonnes (t), which can be translated into a potential carrying capacity of 17.9 M SLUs compared with the current mean 9.36 M SLUs in the survey data of the UK. With the ratio of sheep to cattle at 8.2:25 in the national TSLU, the UK national demands at present consumption levels of cattle and sheep meat can be arithmetically met with pasture grass utilisation rates at or above 65% and 50% by cattle and sheep farming systems, respectively.

Keywords: grassland productivity; cattle; sheep; standard livestock unit; ruminant meat; potential carrying capacity

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1. Introduction

Livestock production systems play an important role in converting natural resources into animal products for human consumption and maintaining other ecological services [1–3]. Grasslands constitute a major part of the agricultural lands in the world and make a significant contribution to food security through the provisioning of the feed requirement of ruminants for meat and milk production [4–6]. The contribution to food security is particularly true in the sense that grass-forage-fed (grazed grass or ensiled forage) livestock systems contribute to food production in cropland-scarce regions or less favourable cropping areas, because

grass can be grown on land unsuitable for crop production [7]. In temperate areas of Northwestern Europe, grasslands occupy up to 50% of agricultural land area, providing up to 75% of fodder for ruminants and therefore playing an essential role in livestock farming systems [8,9]. Overall, grassland areas occupy over 60% of agricultural land areas in the UK, which consists of England, Wales, Scotland, and Northern Ireland [10,11]. In Scotland, Wales, Northern Ireland and in the western part of England, over 75% of the agricultural land are made up of rough grazing and permanent grasslands [12]. It is only in Eastern England where grassland accounted for less than 25% of agricultural land, since this region is suitable and used for arable crop production. All British grasslands are temperate and can be described as various types depending on the respective nature of the grasslands as well as their uses. For examples, they can be wild or cultivated, hill (above 600 m), upland (above 300 m but less than 600 m) or lowland, permanent or temporary, extensive or intensive, and rough grazed or cut to make forage reserves like silage or hay. Of all of the UK grassland areas, 42% are rough grazing, 48% are permanent, and 10% are temporary [2]. Cattle and sheep can efficiently convert these pastures into produce for human consumption while at the same time playing a vital role in nutrient cycling, environmental habitats, and complex food webs that have evolved over millennia.

Most grasslands are infrequently re-sown permanent grasslands and never re-sown rough grazing grasslands in the UK. They are jointly called seminatural grasslands and are characterised by moderate to high biodiversity. Permanent grassland refers to that which is more than five years post-sowing and is moderately productive. Rough grazing grassland is extensively grazed natural grassland with low productivity and usually located in mountainous areas with steep slopes as well as difficult accessibility. Temporary grassland is less than five years old and the most productive; it can be part of a grass ley arable rotation system [13] or be frequently re-sown grasslands where there are normally no arable crops between successive grass ley crops. Improved productivity and quality are the main reasons for re-sowing. Some temporary grasslands are also established from ploughing and re-sowing permanent grasslands that suffer from problems such as poor soil drainage, the invasion of less desirable species, declining yield and quality, and seasonal feed shortage.

A typical grass ley arable rotation has a pasture phase of about five years and an arable phase of two–three years in the UK. Wheat, barley or oat are the usual choices in the arable phase. In the grass crop phase, currently perennial ryegrass (*Lolium perenne*) is the dominantly sown grass species, while timothy (*Phleum pratense*) and white clover (*Trifolium repens*) follow. A higher herbage yield is usually expected from newly established pastures in temporary grasslands. Under cutting management, the yield often decreases over successful years, with the highest yield being in the first harvest year. The decrease from the first to the second harvest year is often greater than that between other years. Newly sown pastures tend to be fertilized with nitrogen (N) at levels close to their economic optimal productivity. Depending on the soil type and environment, the economic level of the N application rate can be up to 300 kg N/ha. Herbage dry matter yield varies according to soil nutrient status, water supply, management (for example, cutting only or grazing only), and weather [14–17]. Empirical weather-based models have been developed and used to estimate the forage dry matter yields for 1 km square grids across the whole of the UK for temporary, permanent, and rough grazing grasslands, accounting for factors such as climate, soil type, atmospheric CO_2 concentration, and technological progress [18,19].

The UK's pasture-dependent ruminant livestock production systems consist of milk, cattle beef, and sheep meat production. Figure 1 shows the predominant regions for dairy, beef, and sheep farming in the lowlands and highlands of the UK.

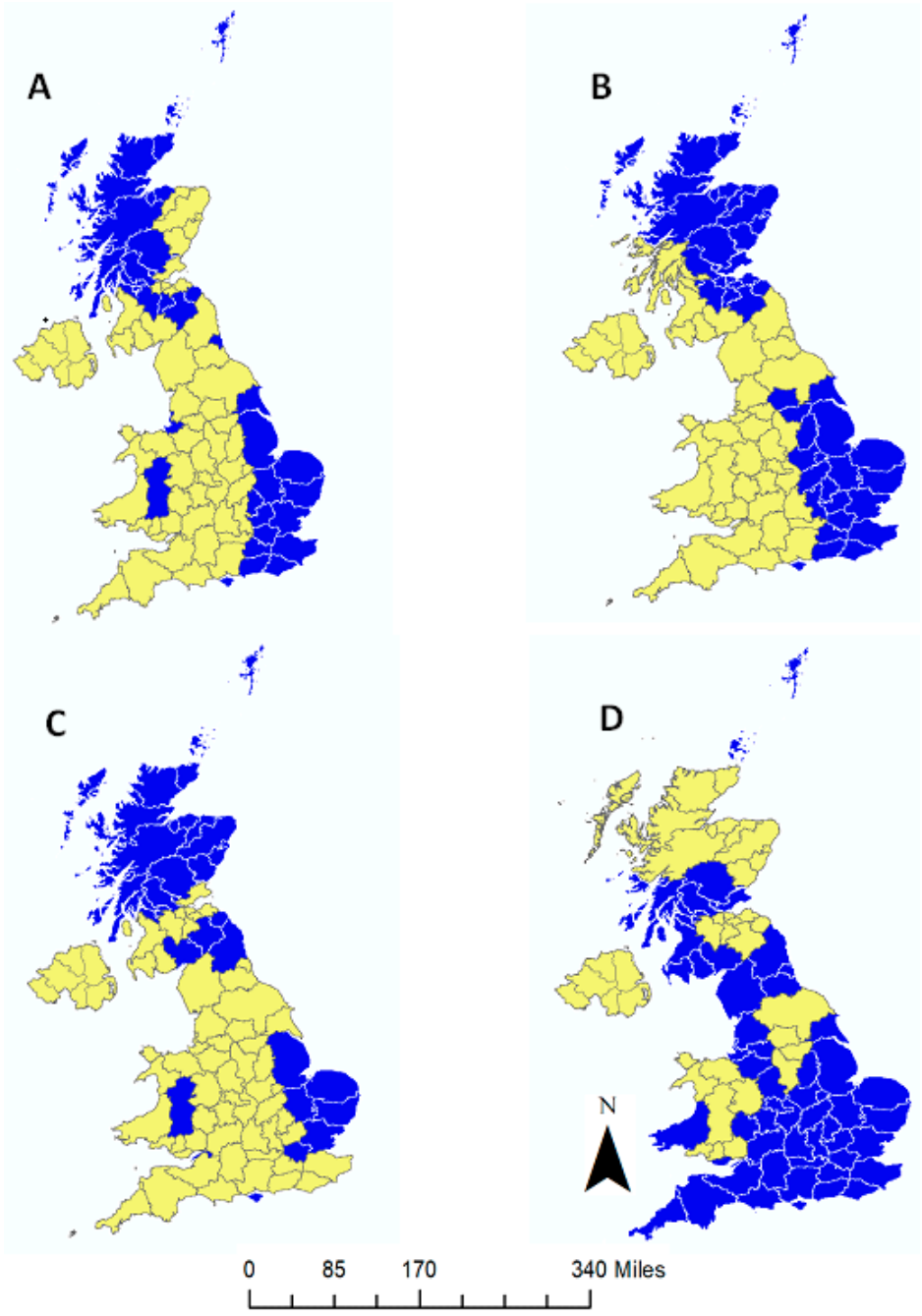

Figure 1. Distribution in regions (coloured in yellow) predominantly used for dairy farming (**A**), beef farming (**B**), and lowland (**C**) as well as highland (**D**) sheep farming in the UK. The scale bar is at the bottom of the maps and the arrow points to the north.

Grassland for dairy farming is mainly temporary grass leys established in rotation with arable crops. The milk yield per dairy cow was, on average, around 8000 L per annum in the three years of 2018 to 2020 [11]. The UK has been completely self-sufficient in fresh liquid milk domestic consumption in the past ten years (i.e., 2011 to 2020). About half of total milk production was dedicated to making cheese and other products. On most dairy farms, more than 50% of cows' metabolizable energy (ME) requirements were met through grazed grass in the months of March–July, or through reserved silage in winter. The usual practice is for dairy herds to be kept outdoors at pasture from spring to autumn (March to November), but kept indoors over winter for three–five months depending on local soil and climatic conditions.

Domestic beef cattle production fulfilled about 86% of net self-sufficiency in terms of total consumption in the UK in 2020 [11]. With total beef production being almost equally shared between suckler and dairy herd production systems (including calves from dairy herds used for fattening). So this is where female dairy calves that are being kept for replacement but turn out to be sub-standard milk producers or those at the end of their productive lives will be slaughtered as cull cows for meat consumption. Also, over the last few years to reduce waste in the dairy industry, among other reasons, the male calves are sold to dairy calf fattening units for meat. It may also be that the dairy cow was crossed with a meat bull for a better-quality calf for meat purposes so the calf can be sold at a higher price. In 2020, 934,859 tonnes (t) of cattle meat in dressed carcass weight were produced, 317,472 t (adjusted to dressed carcass weight) were imported, and 167,538 t were exported, of which about 80% were exported to the European Union (EU). Thus, the total amount of cattle meat available for consumption in the UK (i.e., (import + production) – export) was 1,084,793 t in 2020. Unlike dairy farms, many beef farming was more widely distributed than dairy farming and operated on a wide range of grassland types. Therefore, beef cattle farms can be found in the uplands and marginal areas, such as mountains, moorlands, and lowland dry heaths. Beef farmers in the uplands and marginal areas specialise in rearing suckler calves, which are traded on as store cattle to be fattened to an optimum slaughter weight on better-quality grasslands with supplementary grains or concentrate feeds when necessary. Whereas beef farmers on productive lowland grasslands may operate as fully integrated enterprises, from calf rearing to final slaughter weight. In general, beef cattle production is based on grazing permanent pastures housed over winter, with the cattle being fed hay or silage when grasses are limited for winter grazing, concentrates may also be used for quicker fattening and overwintering feed. At present, the application of mineral fertilizers was generally below the biological optimum for potential herbal dry matter productivity on beef farming grasslands. This being the case, the potential of higher grass productivity when using the full-scale adoption of grass–legume mixture pastures can be considerable under these situations [20]. Consequently, increased grass production can help to extend the grazing season.

Sheep farming is generally a low-cost system in the UK and based on rough grazing permanent pastures in hilly and upland areas, with valley floor fields used to support ewes with young lambs in spring. An important feature in the UK sheep industry is that distinct sheep breeds are stratified depending on the specific environments that they occupy and are adapted to. The sheep of these environments are connected by the movement of lambs and older flocks between highlands and lowlands, involving crossing one sheep breed with another sheep breed. In 2020, sheep meat production fulfilled 109% of net self-sufficiency for domestic consumption in the UK [11]. In 2020, 306,300 t of sheep meat in dressed carcass weight were produced, 79,517 t (adjusted to dressed carcass weight) were imported, and 106,716 t were exported, of which about 90% were exported to the EU. Thus, the total amount of sheep meat available for consumption in the UK was 279,102 t.

The UK agricultural census data are collected, compiled, and made publicly available each year in June by the governmental Department for Environment, Food and Rural Affairs (Defra). Among the agricultural census data were annual total areas of different grassland types, total production, and imports as well as exports of cattle beef and sheep meat in dressed carcass weight. National annual total animal numbers were reported and available for cattle and sheep. The total cattle and sheep populations were also disaggregated into two sex groups, within which subgroups of different ages were further divided.

Using these large datasets for the recent ten years of 2011 to 2020, our objective was to tackle the following research questions:

1. What was the annual variation in areas of different grassland types, populations of different sex/age groups for cattle and sheep, and meat production from cattle and sheep farming?
2. What were the equivalent standard livestock units for all of the animal numbers of cattle and sheep?

3. What was the meat productivity per standard livestock unit in cattle and sheep farming systems?
4. What was the total potential carrying capacity in standard livestock units for all of the UK grasslands?
5. Is it possible that pasture-based-only cattle and sheep farming can produce enough cattle beef and sheep meat to meet the current UK consumption level?

The overall objective was to assess the potential livestock carrying capacity of all grasslands for cattle and sheep in addition to the arithmetic grass forage utilisation rates required to produce enough beef and sheep meat to meet the mean consumption level during 2011–2020 in the UK.

2. Materials and Methods

2.1. Areas of Grasslands

Defra officially publishes areas, in hectares, of temporary, permanent, and rough grazing grasslands each year from the June census in the UK. All agricultural census datasets are available at the GOV.UK website: https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom (accessed on 13 October 2020). The areas of rough grazing grassland were made of common rough grazing and sole right rough grazing grasslands, while the latter also include mountains, hills, heathland, or moorland. UK-wide areas of each grassland type were downloaded and processed into the three grassland types—temporary, permanent, and rough grazing—and selected for the ten years from 2011 to 2020.

2.2. Cattle Beef and Sheep Meat Production

The Defra official agricultural census data contained annual domestic production, imports, and exports for cattle beef as well as sheep meat, all in dressed carcass weight. These datasets were downloaded from the above GOV.UK website in Section 2.1. and selected for the ten years from 2011 to 2020. The annual consumption in the UK for beef and sheep meat was calculated as ((production + import) – export). The UK's beef and sheep meat self-sufficiency was calculated as the ratio of UK annual domestic production to UK annual consumption expressed as a percentage.

2.3. Livestock Populations of Cattle and Sheep

The datasets from the annual June census of UK agriculture contained the total number of cattle (both beef and dairy) and calves as well as the total number of sheep and lambs. For cattle, the animal populations were broken down into male and female groups. In each, the herd was further classed into three age groups: male/female herd under one year old, male/female herd between one and two years old, and male/female herd over two years old. For sheep, the census data classified the sheep population into five groups according to sex and age; these are ewes $\geq$ one year old intended for first-time breeding, ewes $\geq$ one year old intended for further breeding or slaughter, rams over one year old, lambs under one year old, and other sheep over one year old. These data were downloaded from the above GOV.UK website in Section 2.1., selected, and processed for the ten years from 2011 to 2020.

2.4. Standard Livestock Unit (SLU) and Calculating Annual Total Standard Livestock Units (TSLU)

Various definitions are used to describe a reference livestock unit. For example, in the United States of America a reference livestock unit is named an "animal unit" (AU), which is a dry pregnant mature beef cow weighing 500 kilogrammes (kg), with a daily dry matter (DM) intake of one forage intake unit measured at 8.8 kg [21]. In South Africa, an AU is characterised by cattle weighing 450 kg, consuming 10 kg of DM per day and gaining 0.5 kg d^{-1} on a forage diet with a digestible energy concentration of 55% [22]. A tropical livestock unit (TLU) is adopted by the Food and Agriculture Organization (FAO, Rome,

Italy) of the United Nations, which only considers livestock raised in the tropics and is used extensively in the analysis of livestock systems in the tropics [23]. The standard live cattle weight of a TLU is 250 kg.

The standard livestock unit (SLU) used in the EU is usually defined in terms of feed requirements. In the EU's definition, an SLU is a dairy cow weighing 600 kg, producing 3000 litres per year of milk at a 4% fat content, and consuming 19 kg DM d^{-1} without additional concentrated foodstuffs [24]; however, a UK-specific SLU, sometimes referred to as a cow equivalent (CE) [25], is considered as the amount of metabolisable energy (ME) required to maintain a mature 625 kg Friesian cow producing a 40–45 kg calf and 4500 litres of milk at a 3.6% fat content as well as 8.6% non-fat solids per year [20,26]. This is the reference livestock unit definition adopted in this paper. According to Craig [20], one UK SLU requires a total amount of of 48,000 MJ per year. On the basis that one kg of herbal forage DM contains 10.5 MJ of ME, the annual DM intake should then become about 4571 kg of dry matter (i.e., with 365 days for a non-leap year).

To calculate total standard livestock units (TSLUs) per year for all populations of cattle and sheep, the ratios of ME requirements among cattle and sheep between different age groups (i.e., livestock unit conversion coefficients) were used. The accepted livestock unit conversion coefficients in the UK are shown in Table 1 [20,26]. The livestock unit conversion system reflects the energy requirements of different classes of livestock. This information, coupled with data on grassland herbage production and utilisation rate, can be used to calculate potential stocking rates for grazing lands. Meanwhile, adjustments can be made for forage quality, the length of time that livestock are on the farm, and the use of concentrates. For example, one tonne of barley at 87% DM with 11.9 MJ ME per kg of dry matter provides 10,353 MJ ME (i.e., 1000 × 0.87 × 11.9) [25].

Table 1. Livestock unit conversion coefficients relative to the standard livestock unit (SLU) that are used to calculate total SLUs from annual cattle (beef and dairy) and sheep populations in the UK. The corresponding daily metabolisable energy (ME, MJ d^{-1}) and the daily intake (kg d^{-1}) of forage herbal dry matter (DM) with metabolisable energy density at 10.5 MJ (kg DM)$^{-1}$ are shown.

Class of Cattle/Sheep	SLU	MJ d^{-1}	DM (kg d^{-1}) **
Female cattle ≥ 2 Yr	1.00	134.6	12.8
Female cattle 1–2 Yr	0.65	85.5	8.1
Female cattle < 1 Yr	0.34	44.7	4.3
Male cattle ≥ 2 Yr	0.80	105.2	10.0
Male cattle 1–2 Yr	0.65	85.5	8.1
Male cattle < 1 Yr	0.34	44.7	4.3
Ewes ≥ 1 Yr *	0.10	13.2	1.3
Rams ≥ 1 Yr	0.08	10.5	1.0
Lambs < 1 Yr	0.04	5.3	0.5
Other sheep ≥ 1 Yr	0.08	10.5	1.0

* Including ewes ≥ one year old intended for first-time breeding, further breeding, or slaughter, and with a live bodyweight of 70 kg. ** The daily metabolisable energy requirement per SLU was taken from Craig [20]. The daily intake of DM per SLU was calculated by dividing the daily metabolisable energy requirement per SLU by the metabolisable energy density of 10.5; therefore, 134.6 ÷ 10.5 = 12.8 correct to one decimal point.

With the values of livestock unit conversion coefficients in Table 1, for each year the total standard livestock units were calculated for cattle populations as follows:

$$TSLU_c = \sum_{i=1}^{i} CP_i \times CC_i \quad (1)$$

in which $TSLU_c$ is the total cattle *SLU*, CP_i is the cattle population, and CC_i is the livestock unit conversion coefficient in the i^{th} given sex/age class for cattle (in Table 1).

Similarly, the annual total standard livestock units were calculated for sheep populations as follows:

$$TSLU_s = \sum_{i=1}^{i} SP_i \times SC_i \quad (2)$$

in which $TSLU_s$ is the total sheep *SLU*, SP_i is the sheep population, and SC_i is the livestock unit conversion coefficient in the i^{th} given sex/age class for sheep (in Table 1).

2.5. Grassland Herbal Dry Matter Yields and Calculating the UK Potential Carrying Capacity of TSLUs

Large quantities of high-quality forage are necessary in dairy farming because excellent quality is required to fulfil the genetic potentials of dairy cows and maintain profitability in milk production. Due to higher yields and better quality, temporary intensive grasslands and improved permanent extensive grasslands with moderate inputs in areas with good pasture-growing conditions are mostly associated with dairy farms and used for fattening cattle and sheep to slaughter weight. These areas cover the southwest and northwest of England, the lowland grasslands of southern and southwestern Wales, and the lowland areas of Northern Ireland as well as those of southwestern Scotland. Grasslands used for rough grazing are permanent pastures or meadows on marginal lands with small proportions of valuable grasses and legumes due to the invasion of unwelcome species such as thistle, nettle, ragwort and docks. They are, therefore, low in herbal dry matter yields and nutrition. Rough grazing is mainly associated with sheep production and used for beef production. This being the case, sheep production is generally a low-cost system based on permanent pastures and recently sown grass leys.

A significant increase in grassland productivity has been reported on British farms, and the potential to increase grassland herbage output is large if this is needed in the future [27]. The amount of harvested forage dry biomass can vary as much as 10-fold between pastures [2]. Understanding the effects of these factors, such as soil texture types, climate, plant species and varieties, nutrient supply, and management, on grassland productivity is essential in achieving high and stable grassland fodder yields. Seasonality in the forage production of grassland is mainly influenced by weather and soil, which determine the length and intensity of the growing season in a climatic zone. Available ryegrass varieties in the UK can produce annual yields of 17 t ha^{-1} of DM. With high nitrogen inputs, yield improvement through conventional breeding can increase this ryegrass potential yield to 25 DM t ha^{-1} $year^{-1}$ [28].

Empirical weather-based models were developed to calculate herbage DM yields for rough grazing, permanent, and temporary grasslands across the UK [19]. These dry herbage yields were based on cut plots grown with the perennial ryegrass (*Lolium perenne*) in various experiments across the country, and therefore were attainable or potential yields [15–17]. The spatial distribution for 1 km square grids of estimated herbage dry matter yields for permanent, rough grazing, and temporary grasslands was mapped across the UK by Qi [18]. The mean herbal dry matter yield all over the UK for each grassland type was calculated and shown in Table 2. This was carried out by firstly calculating the total grass forage dry matter production for each 1 km square grid for each grassland type using the estimated herbal dry matter yield and grassland area of the related grassland type. All of the grass forage dry matter yields and grassland areas related to the respective grassland type were then aggregated across the UK. The UK-wide average herbal dry matter yield was calculated by dividing the respective total grass forage dry matter production by the respective total areas of respective grassland type. Further details on the development of models and calculating herbal dry matter yields through the use of the models of 1 km square grids can be found in work by Qi [17,18].

Table 2. Average herbal dry matter yield (t ha^{-1}) per year for temporary, permanent, and rough grazing grassland across the UK.

Grassland Type	Herbal Dry Matter Yield
Temporary	12.46
Permanent	8.71
Rough grazing	2.76

These herbal dry matter yields were used to calculate the availability of UK national forage feed production for all grasslands. To calculate the potential carrying capacity of TSLUs (total standard livestock units) of the UK, the standard amount of annual intake per SLU at 4571 kg of herbal dry matter was used on the assumption that one kilogramme of herbal dry matter contains metabolisable energy at 10.5 MJ (kg DM)$^{-1}$ (see Table 1) [20]. The pasture herbal dry matter quality of lowland grasslands or grass leys can be different from that of highland grasslands, but this was not considered in the present calculation.

2.6. Data Analysis

The mean, standard deviation (SD), and coefficient of variation (CV%) were calculated in Microsoft Excel for all of the selected statistical items for the ten years of annual UK agricultural census data from 2011 to 2020. The mean value indicates the magnitude, the SD value indicates the interannual variability from the mean value, and the CV% value indicates the relative interannual variation normalised by the mean value. The illustrative graph figures were made using Sigmaplot 14.0, and the illustrative map was prepared in ArcMap10.8.1.

3. Results

3.1. Variations in Annual Areas of Different Grasslands in 2011–2020

Within these selected ten years, the interannual variations in areas of rough grazing and permanent grasslands were both small with a coefficient of variation (CV) of 1.11% and 2.80%, respectively, while the annual areas of temporary grassland showed a relatively larger variation, with a CV = 8.64 (Table 3). However, the invariable areas of rough grazing and permanent grassland led to a small interannual variation in total areas of all grassland types, with CV = 0.80%. Out of the total grassland area, permanent grassland and rough grazing grassland contributed, on average, 49% and 41%, respectively, while temporary grassland made up the remaining 10% (Table 3). Variation in the annual proportions (%) of the area of each grassland type over the total grassland area followed a similar pattern for the annual areas of the respective grassland type (Table 3).

3.2. Variations in Annual Cattle Numbers and Cattle Standard Livestock Units of Different Sex/Age Groups in 2011 to 2020

The mean total annual cattle population was approximately 9.87 M, and the associated coefficient of variation (CV) was 1.31%, which indicates that the interannual variation in the total cattle population was small in the ten years (Figure 2). An approximately 72% of the mean total cattle population was female, while the remaining 28% was male (Table 4). In the female cattle group, the population was mostly made up of those with an age $\geq$ 2 years old (42.3%), followed by an age of below one year (15.7%). In the male cattle group, the cattle population was mostly made up of those with an age below one year (13.5%), followed by an age between 1 and 2 years old (10.4%) (Table 4). The interannual variation in the cattle population was small from year to year in all six sex/age groups, judging by the small values of CV% (Table 4). The smallest CV% was 1.95 for the female cattle $\geq$ 2 years old, and the largest CV% was 7.23 for the male cattle $\geq$ 2 years old, with the smallest annual population averaged at 36,9497 (Table 4).

Table 3. Annual areas in million hectares (M ha) of rough grazing, permanent, and temporary grasslands in the UK from 2011 to 2020, as well as the means (Mean), standard deviations (SDs), and coefficients of variation (CV%). Figures in brackets are Mean, SDs, and CV% for the proportions in % of areas of respective grasslands over the total grassland area.

Year	Rough Grazing	Permanent	Temporary	Total Grassland Area
2011	5.18	5.88	1.28	12.34
2012	5.13	5.80	1.36	12.28
2013	5.14	5.80	1.39	12.33
2014	5.13	5.82	1.40	12.35
2015	5.00	6.08	1.17	12.25
2016	5.16	6.12	1.14	12.42
2017	5.20	6.14	1.14	12.48
2018	5.09	6.18	1.15	12.42
2019	5.18	6.21	1.19	12.58
2020	5.12	6.12	1.18	12.42
Mean	5.13 (41.4)	6.02 (48.6)	1.24 (10.0)	12.39
SD	0.06 (0.4)	0.17 (1.1)	0.11 (0.9)	0.10
CV%	1.11 (0.9)	2.8 (2.3)	8.64 (9.1)	0.80

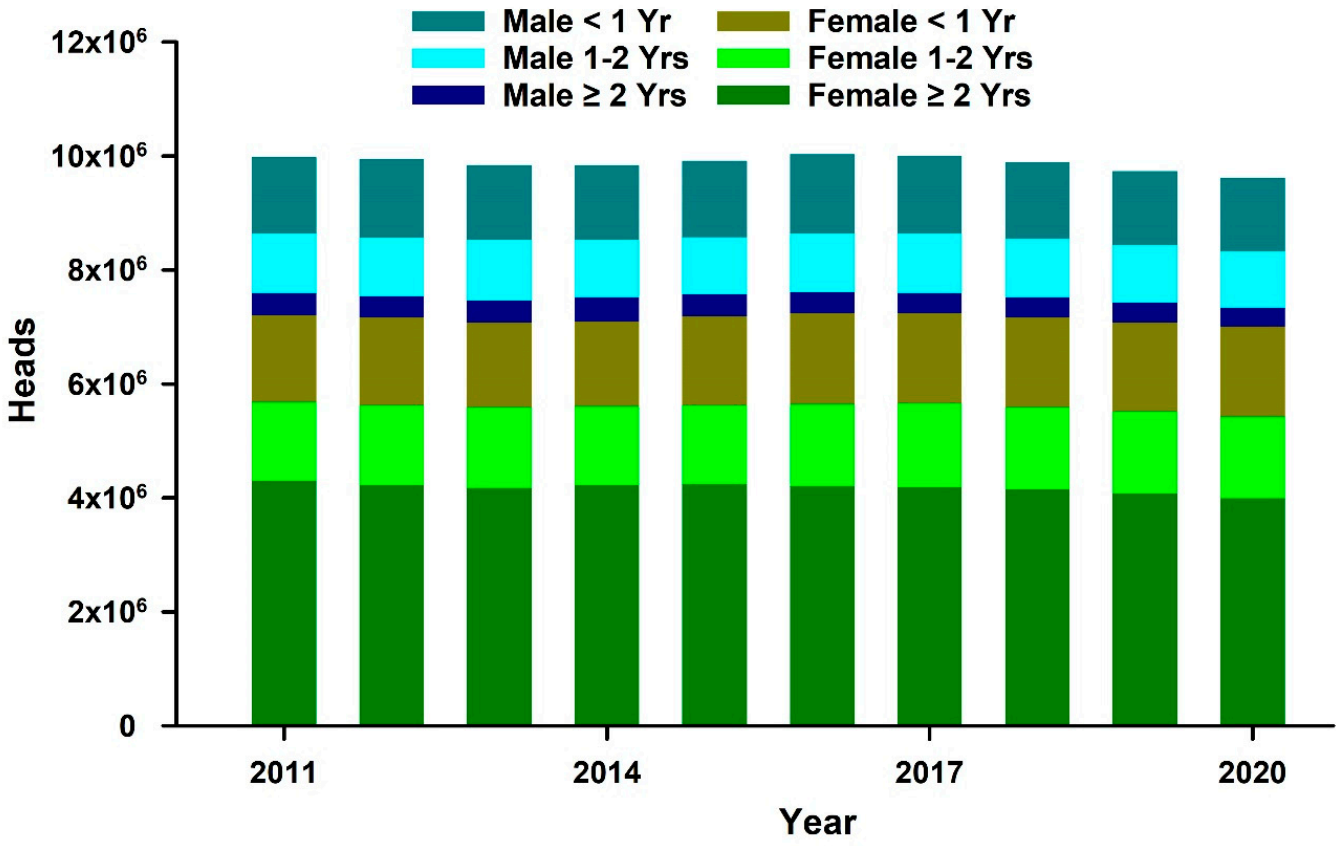

Figure 2. Annual populations of cattle distributed into three age groups of two sex classes from 2011 to 2020 in the United Kingdom.

Table 4. The means (Mean), standard deviations (SDs), and coefficients of variation (CV%) for annual cattle populations of six different sex/age groups from 2011 to 2020 in the UK. Figures in brackets are the Mean, SDs, and CV% for proportions in % of the population of the respective sex/age group over the total cattle population.

Statistic	Female			Male			Total Cattle
	≥2 Yrs	1–2 Yrs	<1 Yr	≥2 Yrs	1–2 Yrs	<1 Yr	
Mean	4,165,701.4 (42.3)	1,418,828 (14.3)	1,558,385.8 (15.7)	369,496.4 (3.75)	1,024,541.2 (10.4)	1,333,204.4 (13.5)	9,870,157.3
SD	81,264.5 (0.53)	31,236.5 (0.38)	38,879.8 (0.43)	26,698.7 (0.25)	23,442.8 (0.18)	36,413.1 (0.21)	131,312.5
CV%	1.95 (1.25)	2.20 (2.69)	2.49 (2.7)	7.23 (6.68)	2.289 (1.78)	2.73 (1.55)	1.33

The annual population of cattle was normalised (i.e., converted) into total standard livestock units (TSLUs) using the livestock unit conversion coefficients relative to the standard livestock units (SLUs) in Tables 2 and 5. The UK national mean annual TSLUs were 7,045,908 and showed very small interannual variation, with a CV = 1.51% in 2011–2020 for cattle (Table 5). Female cattle contributed most of the SLUs (79.9%), while male cattle made up the remaining 20.1%. In the female cattle group, the TSLUs were mostly made up of those with an age ≥ 2 years old (59.3%), followed by those between 1 and 2 years old (13.0%). In the male cattle group, the TSLUs were mostly made up of those between 1 and 2 years old (9.5%), followed by those with an age below one year (6.4%) (Table 5). A proportion of the TSLUs showed small interannual variation in all six sex/age groups, judging by the small values of the CV% (Table 5). The smallest CV% was 0.79 for female cattle ≥ 2 years old, and the largest CV% was 6.21 for male cattle ≥ 2 years old.

Table 5. Annual total standard livestock units (TSLUs) for cattle of different sex/age groups from 2011 to 2020 in the UK and the respective means (Mean), standard deviations (SDs), and coefficients of variation (CV%). Figures in brackets are the Mean, SDs, and CV% for proportions in % of TSLUs of the respective groups over the overall cattle TSLUs.

Year	Female			Male			Overall TSLUs
	≥2 Yrs	1–2 Yrs	<1 Yr	≥2 Yrs	1–2 Yrs	<1 Yr	
2011	4,304,822	891,773	521,039	308,402	682,651	456,728	7,165,416
2012	4,229,230	906,239	526,667	295,254	669,289	469,410	7,096,088
2013	4,177,037	919,154	507,252	307,410	688,964	447,541	7,047,358
2014	4,227,609	892,407	509,705	339,238	657,298	442,745	7,069,003
2015	4,238,467	896,574	533,922	310,117	650,499	456,275	7,085,854
2016	4,204,392	937,478	545,009	291,510	670,873	471,388	7,120,650
2017	4,192,951	951,868	538,113	283,979	683,307	461,465	7,111,684
2018	4,149,039	938,018	535,571	284,313	673,057	453,066	7,033,064
2019	4,078,305	932,925	531,573	284,437	658,115	439,912	6,925,267
2020	3,994,283	925,480	540,848	264,117	642,164	437,804	6,804,696
Mean	4,179,613.5 (59.3)	919,191.7 (13.0)	528,970.0 (7.5)	296,877.67 (4.2)	667,621.8 (9.5)	453,633.3 (6.4)	7,045,908.0
SD	88,349.3 (0.47)	21,430.1 (0.40)	12,770.9 (0.24)	20,540.5 (0.26)	15,306.3 (0.17)	11,722.9 (0.11)	106,325.8
CV%	2.11 (0.79)	2.33 (3.10)	2.41 (3.16)	6.92 (6.21)	2.29 (1.74)	2.58 (1.77)	1.51

3.3. Variations in Annual Sheep Numbers and Sheep Standard Livestock Units of Different Sex/Age Groups in 2011 to 2020

The mean total sheep population was about 33.26 M, and the associated coefficient of variation (CV) was 2.79%. This low CV indicates that the interannual variation in

the total sheep population was small (Figure 3). Characteristically, nearly 50% of the mean total sheep population was lambs under one year of age, while about 40% was ewes ≥ 1 year destined for breeding and slaughter (Table 6). The annual population of these two groups also varied little from year to year, with the CV% being 2.28 and 2.91% in the former and the latter, respectively (Table 6). The groups of rams and other sheep had the lowest populations, accounting for about 1.2 and 1.3% of the total sheep population, respectively. Even though the population of rams was the smallest of the five groups, the ram population and ram proportion out of the total sheep population were stable (the CV% was 3.81 and 3.03%, respectively (Table 6)). The ratio of ewes to rams was also consistently close to 40; that is, for every ram there were ca. 40 ewes.

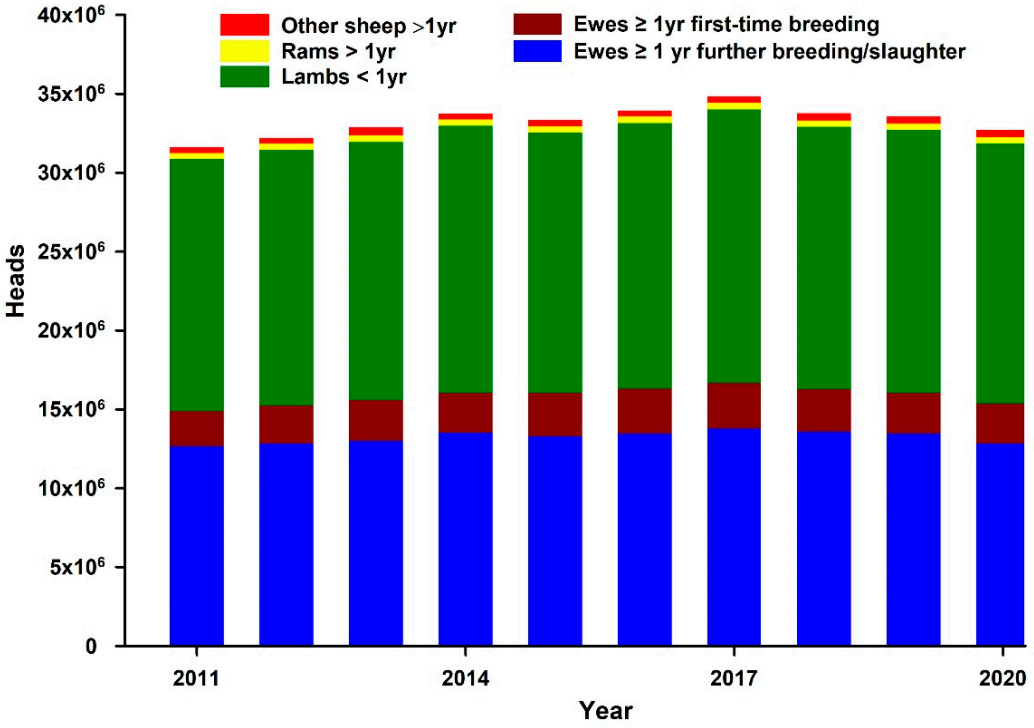

Figure 3. Annual populations of sheep (heads) distributed into five different groups from 2011 to 2020 in the United Kingdom.

Table 6. The means (Mean), standard deviations (SDs), and coefficients of variation (CV%) for annual sheep populations of five different groups from 2011 to 2020 in the UK. Figures in brackets are the Mean, SDs, and CV% for proportions in % of population of the respective group over the total sheep population.

Year	Ewes		Lambs < 1 Yr	Rams > 1 Yr	Other Sheep ≥ 1 Yr	Total Sheep
	≥1 Yr Breeding and Slaughter	≥1 Yr First-Time Breeding				
Mean	13,228,359.0 (39.8)	2,608,892.8 (7.8)	16,602,444.7 (49.9)	406,517.9 (1.2)	415,554.2 (1.3)	33,261,768.6
SD	384,912.4 (0.29)	202,440.8 (0.45)	380,151.7 (0.43)	15,481.8 (0.04)	44,827.7 (0.14)	928,878.2
CV%	2.91 (0.75)	7.76 (5.8)	2.28 (0.86)	3.81 (3.03)	10.78 (11.09)	2.79

By applying the livestock unit conversion coefficients in Table 1, the annual population of sheep was converted into total standard livestock units (Table 7). The UK annual mean sheep TSLUs were 2,313,589 and showed small interannual variability, with a CV = 3.07%

(Table 7). Ewes accounted for approximately 68.4% of the TSLUs, while lambs made up 28.7% of the TSLUs (Table 7). In the ewe group, ewes destined for further breeding and slaughter contributed 57.2% of the TSLUs. Rams and other sheep contributed the least to the TSLUs (Table 7). Proportions of the sheep TSLUs showed small interannual variability in the five groups, judging by the small values of the CV% (Table 7). The smallest CV% was 0.71 for the ewes destined for further breeding and slaughter, and the largest CV% was 10.99% for the other sheep group, which accounted for only 1.4% of the sheep TSLUs (Table 7).

Table 7. Annual total standard livestock units (TSLUs) for sheep of five different groups from 2011 to 2020 in the UK and the respective means (Mean), standard deviations (SDs), and coefficients of variation (CV%). Figures in brackets are the proportions in % of the TSLUs of respective groups over the overall sheep TSLUs.

Year	Ewes		Lambs < 1 Yr	Rams > 1 Yr	Other Sheep ≥ 1 Yr	Overall TSLUs
	≥1 Yr Breeding and Slaughter	≥1 Yr First-Time Breeding				
2011	1,264,435	222,413	639,580	30,218	31,861	2,188,507
2012	1,279,859	243,086	649,177	31,353	29,131	2,232,606
2013	1,299,757	256,372	655,237	34,578	38,562	2,284,507
2014	1,351,478	251,133	677,441	33,395	29,102	2,342,549
2015	1,327,778	274,594	661,117	32,636	30,161	2,326,285
2016	1,346,006	284,383	673,619	32,743	31,108	2,367,859
2017	1,376,198	290,745	693,614	33,338	32,439	2,426,334
2018	1,357,156	271,399	664,845	32,571	37,361	2,363,332
2019	1,343,968	259,537	666,897	32,964	36,809	2,340,174
2020	1,281,723	255,230	659,452	31,419	35,910	2,263,734
Mean	1,322,835.9 (57.2)	260,889.3 (11.3)	664,097.8 (28.7)	32,521.4 (1.4)	33,244.3 (1.4)	2,313,588.7
SD	38,491.2 (0.41)	20,244.1 (0.59)	15,206.1 (0.36)	1238.5 (0.04)	3586.2 (0.16)	71,003.0
CV%	2.91 (0.71)	7.76 (5.21)	2.29 (1.26)	3.81 (2.93)	10.79 (10.99)	3.07

3.4. Variations in Annual Meat Production from Cattle and Sheep in 2011 to 2020

The mean annual production of cattle meat in dressed carcass was 897,377 t, and the associated CV% was 3.33; the mean annual production of sheep meat was 303,399 t, and the associated CV% was 2.80 (Table 8). The small values of CV% signified little interannual variations and thus stability in both cattle beef and sheep meat production domestically in 2011 to 2020. The mean annual import and export were 325,998 and 145,174 t, respectively, for cattle meat, while the import and export were 103,447 and 105,061 t, respectively, for sheep meat. The import of cattle meat was always larger than the export, while the export and import of sheep meat were more balanced. The annual imports and exports showed slightly large annual variations, judging by the CV% values for both cattle beef and sheep meat (Table 8).

The mean annual national consumption of cattle meat was 1,078,201 t, and the associated CV% was 3.09; the mean annual national consumption of sheep meat was 301,785 t, and an associated CV% was 5.57. The mean self-sufficiency for cattle meat indicates that cattle beef production met about 83% of the domestic consumption demands (Table 8). Although sheep meat production, on average, can self-sufficiently meet 100% of domestic consumption demands, there were a couple of years (i.e., 2015 and 2016) in which production fell short (Table 8).

Table 8. Annual production, import, export, domestic consumption (t), and self-sufficiency of cattle beef and sheep meat from 2011 to 2020 in the UK, as well as the respective means (Mean), standard deviations (SDs), and coefficients of variation (CV%).

Livestock	Year	Production	Import	Export	Consumption	Self-Sufficiency *(%)
Cattle	2011	931,478	301,735	170,826	1,062,388	87.7
	2012	876,928	305,122	142,147	1,039,903	84.3
	2013	840,228	309,428	126,241	1,023,414	82.1
	2014	871,373	325,992	136,715	1,060,650	82.2
	2015	880,410	342,526	128,397	1,094,539	80.4
	2016	916,443	331,388	139,948	1,107,883	82.7
	2017	904,344	344,427	132,894	1,115,877	81.0
	2018	900,574	364,725	139,918	1,125,380	80.0
	2019	917,132	317,168	167,119	1,067,182	85.9
	2020	934,859	317,472	167,538	1,084,794	86.2
	Mean	897,377	325,998	145,174	1,078,201	83.3
	SD	29,867.61	19,975.93	16,885.66	33,307.86	2.64
	CV%	3.33	6.13	11.63	3.09	3.17
Sheep	2011	300,740	109,609	111,361	298,988	100.6
	2012	285,717	105,990	108,419	283,289	100.9
	2013	300,323	119,732	119,343	300,712	99.9
	2014	306,316	112,072	116,142	302,245	101.4
	2015	309,496	114,834	90,802	333,527	92.8
	2016	300,087	115,520	90,974	324,632	92.4
	2017	308,785	100,398	103,401	305,783	101.0
	2018	298,521	97,280	96,677	299,124	99.8
	2019	317,701	79,518	106,772	290,446	109.4
	2020	306,301	79,518	106,716	279,102	109.7
	Mean	303,399	103,447	105,061	301,785	100.8
	SD	8508.72	14,344.73	9764.89	16,822.45	5.67
	CV%	2.80	13.87	9.29	5.57	5.63

* The self-sufficiency ratio (%) for domestic consumption was calculated as [(production + import) − export)]/production × 100.

3.5. Variations in Annual Cattle and Sheep Meat Productivity Per Standard Livestock Unit in 2011 to 2020

With the annual total SLUs for cattle in Table 5 and sheep in Table 7, and the annual cattle and sheep meat production in Table 8, meat productivity, measured in kg of dressed carcass weight per standard livestock unit, was calculated (Table 9). For the cattle industry, the mean annual meat productivity was 127.4 kg/SLU, with a CV% of 4.07; the mean annual meat productivity was 131.2 kg/SLU, with a CV% at 3.11, for the sheep industry (Table 9).

3.6. The Potential Carrying Capacity in Total Standard Livestock Units from All Grasslands in the UK

By multiplying the UK-wide mean forage herbal dry matter yields of temporary, permanent, and rough grazing grasslands in Table 2 with the respective areas in Table 3, the potential availability of annual herbal dry matter production was computed (Table 10). The mean annual total herbal dry matter was rather stable, at about 82 M t, with a small associated CV% of 0.68 (Table 10). Among the three grassland types, permanent grassland contributed most of the total pasture dry matter production (ca. 64%), while temporary and rough grazing grassland, respectively, accounted for ca. 19 and 17% of total pasture dry matter production (Table 10). Based on the annual consumption per SLU of 4571 kg of herbal dry matter containing 10.5 ME MJ/kg, the potential carrying capacity of total SLUs can be estimated (Table 10). The mean annual total SLUs can reach approximately 18 M, with a small associated CV% of 0.68 (Table 10). The contribution of respective grasslands

to the total SLUs followed the proportional contribution to the total pasture dry matter production (Table 10).

Table 9. Annual cattle and sheep meat productivity in kg of dressed carcass weight per unit of standard livestock unit (kg/SLU) from 2011 to 2020 in the UK.

Year	Cattle	Sheep
2011	130.0	137.4
2012	123.6	128.0
2013	119.2	131.5
2014	123.3	130.8
2015	124.3	133.0
2016	128.7	126.7
2017	127.2	127.3
2018	128.1	126.3
2019	132.4	135.8
2020	137.4	135.3
Mean	127.4	131.2
SD	5.19	4.08
CV%	4.07	3.11

Table 10. Estimated annual potential pasture dry matter availability (tonnes, t) of temporary (TG), permanent (PG), and rough grazing (RG) grasslands, as well as the respective potential carrying capacity in standard livestock units (SLUs) from 2011 to 2020 in the UK, together with the associated means (Mean), standard deviations (SDs), and coefficients of variation (CV%). Figures in brackets are the proportions in % of dry matter or SLUs of respective grassland types over the UK total dry matter availability or total SLUs.

Year	Herbal Dry Matter (t)				SLU			
	TG	PG	RG	Total	TG	PG	RG	Total
2011	15,923,880	51,188,670	14,296,800	81,409,350	3,483,675	11,198,571	3,127,718	17,809,965
2012	16,908,220	50,509,290	14,147,760	81,565,270	3,699,020	11,049,943	3,095,113	17,844,076
2013	17,319,400	50,535,420	14,180,880	82,035,700	3,788,974	11,055,660	3,102,358	17,946,992
2014	17,394,160	50,727,040	14,156,040	82,277,240	3,805,329	11,097,580	3,096,924	17,999,834
2015	14,540,820	52,939,380	13,800,000	81,280,200	3,181,103	11,581,575	3,019,033	17,781,711
2016	14,254,240	53,287,780	14,241,600	81,783,620	3,118,407	11,657,795	3,115,642	17,891,844
2017	14,254,240	53,435,850	14,354,760	82,044,850	3,118,407	11,690,188	3,140,398	17,948,994
2018	14,353,920	53,810,380	14,048,400	82,212,700	3,140,214	11,772,124	3,073,376	17,985,714
2019	14,864,780	54,062,970	14,305,080	83,232,830	3,251,975	11,827,384	3,129,530	18,208,889
2020	14,715,260	53,287,780	14,125,680	82,128,720	3,219,265	11,657,795	3,090,282	17,967,342
Mean	15,452,892 (18.8)	52,378,456 (63.9)	14,165,700 (17.3)	81,997,048	3,380,637 (18.8)	11,458,861 (63.9)	3,099,037 (17.3)	17,938,536
SD	1,307,895.1 (1.61)	1,453,263.8 (1.65)	159,116.1 (0.18)	554,229.3	286,128.9 (1.61)	317,931.3 (1.65)	34,809.9 (0.18)	121,249.1
CV%	8.46 (8.54)	2.77 (2.57)	1.12 (1.05)	0.68	8.46 (8.54)	2.77 (2.57)	1.12 (1.05)	0.68

3.7. Is It Possible That Pasture-Based-Only Cattle and Sheep Systems Can Produce Enough to Satisfy the UK's Current Ruminant Meat Demands?

According to Craig [20], different grazing systems have different pasture herbage utilisation rates. For example, the set stocking system has the lowest utilisation rate, at 50%, but the paddock system has the highest utilisation rate, at 80%, while the rotational system has an intermediate utilisation rate, at 65%. Here, a range of utilisation rates, from 50 to 100%, were applied to the total pasture herbal dry matter availability in Table 10 irrespective of the grazing systems to estimate the UK national SLUs against the current

mean annual total SLU converted from populations of cattle and sheep in the agricultural census data by Defra (Figure 4). The share of the total SLUs between the cattle and sheep sectors, shown in Figure 4, was calculated based on the mean ratio of sheep SLUs in Table 7 over cattle SLUs in Table 5. It was determined that, approximately, the ratio of total sheep SLUs to total cattle SLUs was 8.2:25 (i.e., approximately 24.7% of the overall total SLUs was made up of sheep).

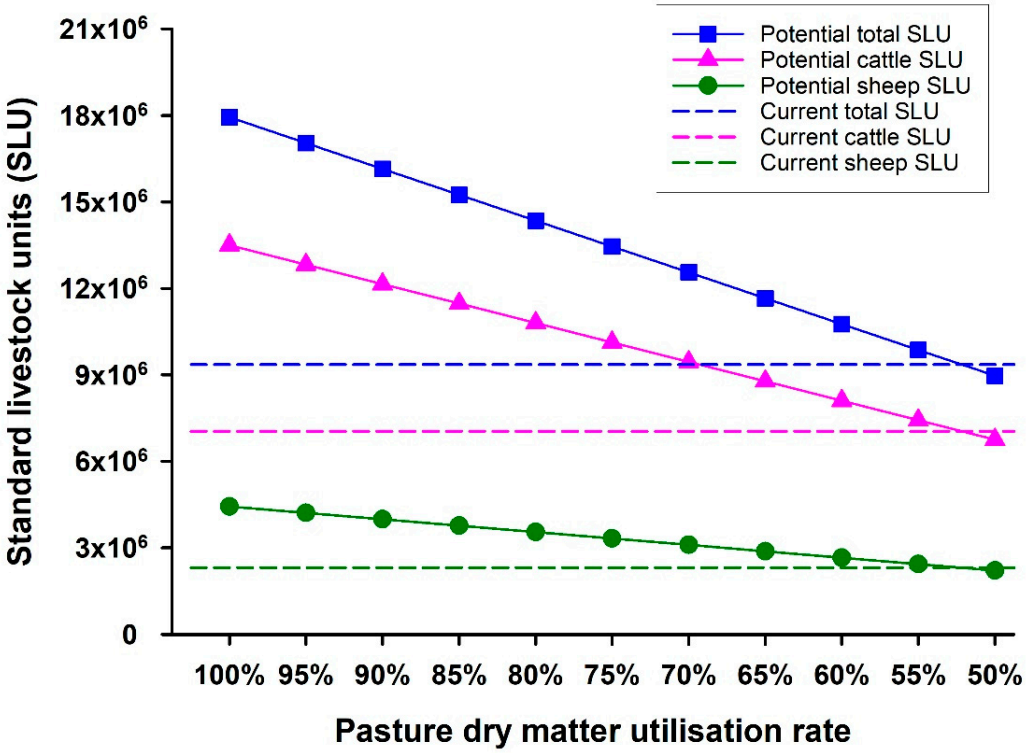

Figure 4. The UK national potential standard livestock unit (SLU) carrying capacity at a 100% pasture herbal dry matter utilisation rate and at various decreasing utilisation rates (blue squares). The shares of cattle (pink triangles) and sheep (green circles) SLUs were calculated using the ratio of the mean proportion of sheep to cattle SLUs from 2011 to 2020. The pink dashed line is the current UK mean total cattle SLUs from 2011 to 2020 calculated from the cattle populations, while the green dashed line is the current UK mean total sheep SLUs from 2011 to 2020 calculated from the sheep populations (see Tables 5 and 7). The blue dashed line is the current UK mean total SLUs from 2011 to 2020 summed from the current UK mean cattle and sheep SLUs from 2011 to 2020.

It was apparent from Figure 4 that the potential pasture biomass production at forage utilisation rates above 55% can meet the present annual herbage feed needs for combined cattle and sheep total SLUs in the UK. It is even the case that 24.7% of total SLUs for sheep can be met at forage utilisation rates close to 50%, but the other 75.3% of total SLUs for cattle required forage utilisation rates equal or above 55% to be met.

Applying the cattle and sheep meat productivity at 127.4 and 131.2 kg per SLU, respectively, in Table 9, and the respective total SLUs in Figure 4, UK national cattle and sheep meat production can be estimated against current mean cattle and sheep meat production and consumption in 2011 to 2020 (Figure 5). If the current levels of imports and exports of cattle meat in 2011 to 2020 remain unchanged (i.e., cattle meat production does not need to fill the gap due to greater imports than exports), UK cattle meat production requirements can be met by pasture fodder utilisation rates at or above 55%; however, if the extra amount of cattle meat imports needs to be offset by domestic production and the present consumption level is maintained, this level of domestic cattle meat production requirements can be met by pasture herbal utilisation rates at or above 65% (Figure 5). The level of annual domestic sheep meat production was a good match with UK consumption

from 2011 to 2020. As such, the demand for present levels of sheep meat production and consumption can be met by pasture grass utilisation rates at or above 50% (Figure 5).

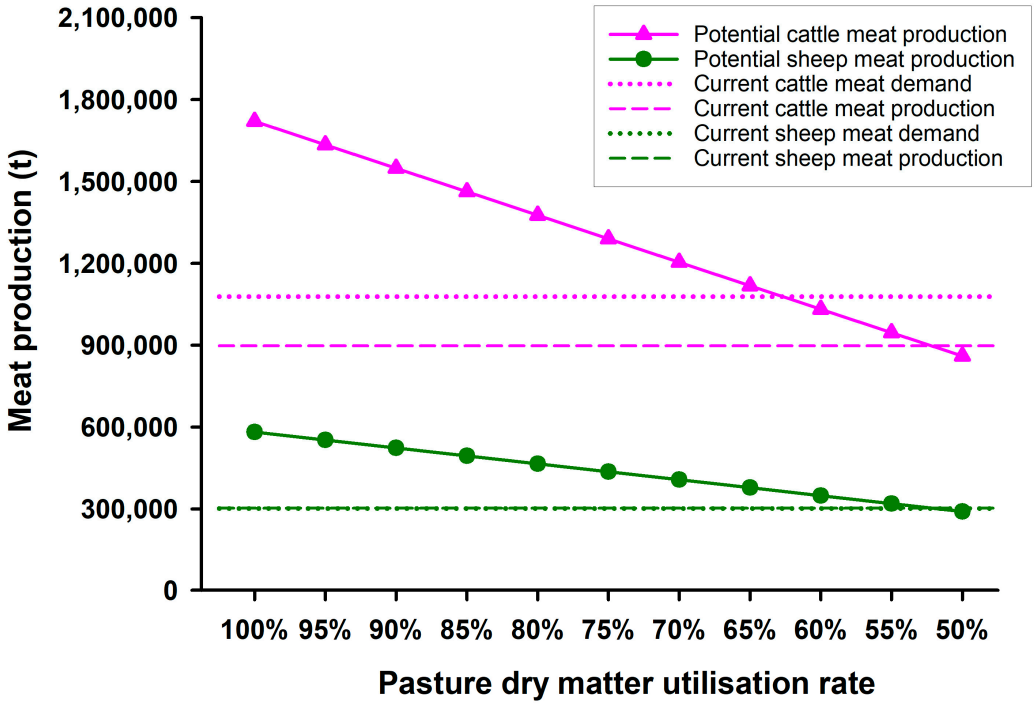

Figure 5. The national UK potential meat production capacity in dressed carcass weight (t) of cattle (pink triangles) and sheep (green circles) farming systems based on the standard livestock unit (SLU) carrying capacity at various pasture herbage utilisation rates (see Figure 4). The pink dotted line is the UK mean cattle meat consumption level from 2011 to 2020, and the pink dashed line is UK mean cattle meat production from 2011 to 2020 (Table 8). The green dotted line is the UK mean sheep meat consumption level from 2011 to 2020, and the green dashed line is UK mean sheep meat production from 2011 to 2020 (see Table 8). Because the UK mean sheep meat production and consumption were almost the same (see Table 8), the green dotted and dashed lines happen to overlap.

4. Discussion

To the best of our knowledge, this is the first time that the data on cattle, sheep, and grassland from the Defra agricultural census have been synthesised, analysed, and assessed in the way presented in this study. This made it plausible to explore the possibility to produce cattle and sheep meat with pasture-based-only diets to meet domestic demands at current consumption levels in the UK. Importantly the concept and definition of the UK-specific standard livestock unit (SLU) were used to standardise the national populations of different sex/age groups in cattle and sheep to the total standard livestock units (TSLUs). The normalisation of animal populations into TSLUs on a UK scale allows us to establish a baseline with which to calculate meat productivity per SLU for the cattle and the sheep farming industries. Only the cattle and sheep sold and slaughtered in abattoirs directly contributed to domestic meat production and the food supply chain; however, on the continuity line of beef and sheep meat production and supply, the other unslaughtered animals in the livestock population played a collective and integral part in indirectly contributing to meat production. The respective estimates of meat productivity per SLU for cattle and sheep were then used to assess options of ruminant meat carrying capacity to meet national demands at the current consumption level. These baseline estimates of meat productivity per SLU could also be used by policymakers to help to address ruminant meat carrying capacities to meet local demands [29].

The concept and definition of an animal unit (AU) were used to assess how much pastureland was required to meet demands for cattle meat in Brazil [30]. It was found that

improving the productivity of pastureland from 32–34% to increase productivity at 49–52% of the potential carrying capacity would be sufficient to meet demands for meat and spare land for other uses, such as food crops, wood products, and biofuels, without the need to convert natural ecosystems in Brazil. The concept and definition of the specific European Union standard livestock unit (LSU) were adopted to model changes in potential grassland productivity and grass-fed livestock density in response to climate change at a European scale [31], as well as in assessing the effects of integrating land-use and ecosystem services into a bioenergy value chain optimisation framework [32].

At a UK national scale, cattle farming systems have resulted in mean meat productivity of 127.4 kg/SLU, with a CV = 4.07%, while the sheep farming systems have yielded mean meat productivity of 131.2 kg/SLU, with a CV = 3.11%, in 2011 to 2020 (Table 9), suggesting that the sheep farming systems had higher productivity than cattle farming systems by 3.8 kg/SLU. However, 75% and 70% of the fresh dressed carcass weight were edible products, and 21% and 20% of the fresh edible products were crude protein for cattle and sheep, respectively [5]. Therefore, after taking these percentage values into consideration, the cattle and sheep farming systems yielded protein productivities of 20.1 kg/SLU and 18.4 kg/SLU, respectively, showing that the former had higher protein productivity than the latter by 1.7 kg/SLU. This analysis was crude and on a national scale because of the nature of the agricultural census data, and so it cannot allow the revelations of the granular details of how individual livestock farmers fed and managed the animals on their farms.

The small interannual variability in the meat and protein productivities per SLU in the ten years of 2011 to 2020 suggests stagnations in productivities per SLU or that the improvements in cattle and sheep genetic performance or management were small. This is reflected in the small change in the mean annual dressed carcass weight in 2011 to 2020 for both the sheep and cattle sectors, with survey data available from [11]. For sheep, the average dressed carcass weight was 19.4 kg with a CV = 1.61% for lambs and 26.3 kg with a CV = 2.27% for ewes and rams. For cattle, the average dressed carcass weight was 347.2 kg with a CV = 1.24% for steers, heifers, and young bulls and 311.0 kg with a CV = 1.43% for cows and adult bulls. This being the case, the small CV values suggest that the dressed carcass weight was very consistent from year to year from 2011 to 2020 for both cattle and sheep.

Since rough grazing grassland is seminatural and has undergone little or no changes in its use, it is not surprising that its area was stable and had the lowest annual variation measured by the coefficient of variation (CV = 1.11%). The temporary grassland had a turnover rate of every five years, and its area had relatively higher annual variation (CV = 8.64%). Even though the rough grazing grassland area (5.13 M ha) was more than four times larger than the temporary grassland area (1.24 M ha) (Table 3), the temporary grassland still provided a slightly larger proportion of the total potential herbage dry matter than the rough grazing grassland (i.e., 18.8 versus 17.3%, Table 10) because of the 4.5-fold difference in the forage dry matter yield between the two grassland types (Table 2). The disparity in the grass forage productivity between grassland types in Table 2 can be ecologically exploited to release rough grazing grassland for other uses when part of the permanent grassland is converted into temporary grassland, for example [18].

Grass forage is the cheapest source of animal feed for cattle and sheep. This may be one of the reason, pasture-based livestock farming systems are presently dominant in many parts of the UK. Because of its maritime climate, the UK can take full advantage of a long grazing season and high grass forage yields coupled with high metabolisable energy. Open pasture-based production systems are known to be more competitive, with lower costs, than systems involving year-round housing. However, mixed environmental impacts have been reported with grass-forage-fed livestock diets with reports increasing greenhouse gas emissions of CH_4, but decreasing CO_2 and having no impact on N_2O [33]. Grazing systems also provide a better image of animal-derived food production to consumers [34], possibly providing yet another reason for the use of pastures. But, grass forage feed quality varies with the grass developmental stages. Mature grass contains more dry matter but

less metabolisable energy, protein, and fat than young leafy grass. Grass nutrients are therefore digested less efficiently when grass is at advanced stages. If cattle and sheep are grazing mature grass then they may need greater feed intake of this grass, or concentrates may be required, to meet nutritional requirements for the maintenance of optimal body health and functions. Although a recent review concluded that there was no evidence found regarding the impact of grass-based-only diets on final livestock liveweights, but that livestock growth rates can be slower on grass only diets compared with cereal-based ones [33]. This means that grass-pasture-based cattle and sheep may take longer to reach the required functional or slaughter liveweights [35–37]. However, concentrate feed is critical in the current ruminant farming systems in the UK, since it is required in maintaining lactating cows and early weaned calves, or ewes bearing two or more lambs. Concentrates are also used for finishing or winter feed when fodder feed is in short supply on grasslands.

In the UK, the cattle and sheep sectors use significant supplementation of concentrates in the current livestock farming systems. From 2011 to 2020, the average annual concentrates fed to cattle and calves were 5,239,041 t with CV = 4.47% and those fed to sheep were 841,177 t with CV = 9.49%. On the basis that the grain concentrates, normally consists of barley, maize, oats, rye, or wheat, with metabolisable energy (ME) of 11.9 MJ/kg at 87% dry matter [25], the combined usage of concentrates for cattle and sheep (i.e., 5,239,041 + 841,177 = 6,080,218 t) should contain 7.2355×10^{10} MJ ME. One standard livestock unit requires 48,000 MJ ME per year [20]. As a result, this annual feed of concentrates could support about 1,507,387 SLUs. The current annual mean combined total cattle and sheep LSUs were 9,359,497 (see Tables 5 and 7). This being the case, the metabolisable energy in the annual feed of concentrates could apparently support 16.1% of the combined cattle and sheep SLUs in the UK agricultural census data (i.e., (1,507,387/9,359,497) $\times$ 100 = 16.1%)).

Grass is an important source of feed given to cattle and sheep in the UK. Pasture is used as an important component in the growing trend of regenerative agriculture. At present, relatively few cattle and sheep are 100% grass-fed via grazing and/or the use of conserved pasture, such as silage. By 2019, there were 500 members in the Pasture-Fed Livestock Association (PFLA) after its initiation in 2009 in the UK [38]. These members were devoted to producing ruminant meat and milk from animals fed exclusively on pasture. In 2015, the grassland area managed to *Pasture for Life* standards (i.e., 100% grass-fed) reached 10,000 hectares of grassland, while the area kept increasing [38]. However, according to Wilkinson [34], the typical proportion of forage-fed dry matter in the total diet is 76.8, 72.0, and 86.4% for beef cattle, dairy cattle, and sheep, respectively, in the UK livestock production systems. Pasture-based-only cattle and sheep farming systems have been reported to be less intensive but more sustainable. Therefore, they offer great potential to restore ecosystem services, build resilience to climate change, and support the transitional pathway of the UK government to their net-zero greenhouse gas emissions target by 2050 [39,40].

Our analyses, based on the potential availability of total herbage biomass from all grasslands, showed that the forage feed requirements for the present annual cattle and sheep combined total SLUs in the UK can potentially be met more than adequately when the pasture forage utilisation rate was at 55% or above (Figure 4). In the ten years of 2011 to 2020, the average normalised total SLUs combined from cattle and sheep populations was 9,359,497 in the UK agricultural census data, while the potential total SLU carrying capacity of all grasslands was 17,938,536 (Table 10). That means that the current combined cattle and sheep total SLUs were just 52.2% of the potential total SLU carrying capacity. Having used the UK SLU for these calculations where one UK SLU is equal to a dairy cow with 4500 litres of milk and a 40–45kg calf, the total carrying capacity calculated in this study is an optimistic estimate. As a typical dairy cow in the UK currently probably has a UK SLU above one as they are producing over 8000 litres a year whilst the SLU for a beef cow is slightly below one. With roughly equal populations in the different groups this may balance out, but we still expect it to lean towards an overestimation of the carrying capacity, hence the suggestion of it being an optimistic estimation. This highlights

a limitation of the definition and use of the UK SLU with the current milk production levels, which we recommend reevaluating. What is further important to consider is that the population numbers used from the Defra database to calculate the carrying capacity in relation to meat production is that of all cattle, so it includes dairy cows. As the dairy industry is an important source of meat it was felt important to keep these in, however no correction factor has been included as the dairy calves to be sold as meat would have moved into the beef system. The bigger discrepancy is with the non-pregnant (barren), low yielding cull cows that do not need as much nutrition and therefore create a "free" flow of meat, not requiring additional carrying capacity. This dynamic would make our estimate conservative and combined with the optimistic evaluation above, it may cancel each other out. This is, however, a claim that carries a level of uncertainty.

In the UK, grasslands are also used as feed sources for goats, horses, and farmed deer. For the ten years from 2011 to 2020, the average annual populations for goats, deer, and horses were 103,137 (CV = 5.95%), 32,887 (CV = 7.69%), and 276,913 (CV = 10.33%), respectively. According to Craig [20], the livestock unit conversion coefficients relative to the standard livestock unit are 0.15, 0.3, and 0.8, respectively, for goats, farmed deer, and horses; the respective average annual standard livestock units were then 15,741, 9866, and 221,531, totalling 246,867 SLUs. As each SLU consumes 4571 kg of herbage dry matter, on average, those goats, farmed deer, and horses combined would need approximately 1.13 M t of herbage dry matter. If the pasture forage utilisation rate was as low as 50%, a double amount of 2.26 M t of herbage dry biomass would be required to sustain all goats, deer, and horses. This 2.26 M t of dry matter represented about 2.8% of the total potential annual availability of ca. 82 M t (Table 10). This should not significantly affect the capability to adopt herbage-based-only diets for cattle and sheep farming practices to meet the current domestic ruminant meat consumption demands in the UK.

In the analysis of domestic sheep meat production, to meet the current level of the UK's consumption of sheep meat, pasture forage utilisation rates at or above 50% of the potential availability of herbal biomass would be sufficient (Figure 5). A figure of 50% is an undemandingly low pasture forage utilisation rate; this may be why the UK was comfortably self-sufficient for most of these years in terms of meeting domestic sheep meat consumption (Table 9). In the case of the current level of cattle meat consumption, the imports of cattle meat were, on average, twice as much as exports from 2011 to 2020 in the UK (Table 9). Our analysis showed that if the extra amount of cattle meat imports was offset by domestic production and the present consumption level was maintained, pasture grass utilisation rates at or above 65% of the potential availability of herbal biomass would be necessary to enable cattle farming systems to produce enough meat to satisfy the current national demands (Figure 5); however, it must be pointed out that extreme weather events, such as floods or a prolonged duration of drought, coupled with high temperature, will likely reduce grassland forage yields, leading to potential feed shortages when cattle and sheep farming systems solely rely on herbage diets [41,42]. These factors were not considered here, even though they can have extreme effects on any agricultural systems. Also this is solely on production capacity and does not consider any greenhouse gas emissions or other factors.

5. Conclusions

This study has shown that the total availability of herbage dry matter of all grasslands can support a national potential carrying capacity for cattle and sheep to produce sufficient ruminant meat to meet UK domestic needs with undemanding pasture utilisation rates if consumption per capita stayed at current levels. Pasture not only supplies sustainable feed to ruminants but also plays a potential role in greenhouse gas mitigation, preserving soil fertility, and combatting soil erosion on steep slopes due to its ecosystem services. The adoption of grass-fed-only diets for cattle and sheep farming may offer potentials to support the transitional pathway of the UK government to their net-zero greenhouse gas emissions target by 2050. This is a high level capacity assessment but implementing

and practicing grass-fed-only cattle as well as sheep farming systems may be complicated because it can involve major changes for governmental policies and farmers such as land use, livestock product certifications, and herd characteristics. The approach adopted in this paper can be expanded by including nutritional aspects, such as crude protein content in pasture, for a more complex analysis with these large, interrelated sets of long-term time series data collected by the UK government. Additionally, it could be adapted to include different management practices and account for livestock diseases.

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