WWF

FOR YOUR WORLD

THE FUTURE OF FEED:

HOW LOW OPPORTUNITY COST LIVESTOCK FEED COULD SUPPORT A MORE REGENERATIVE UK FOOD SYSTEM

This report is the second in WWF-UK's 'Future of Feed' series. Part one, 'A WWF Roadmap to Accelerating Insect Protein in UK Feeds' is available via our web site.

ACKNOWLEDGEMENTS

Authors

3Keel
Julian Cottee, Caitlin McCormack, Ella Hearne, Richard Sheane. Design by Robbie Dawson, Richard Scott

The authors would like to acknowledge the guidance, comments and suggestions provided by a large number of WWF contributors in putting together this report.

WWF Team
Piers Hart, Mollie Gupta, Sabrina Goncalves Krebsbach, Callum Weir, Sarah Halevy, David Edwards, Pete Pearson

Additional thanks to:

Hannah van Zanten, Renee Cardinaals and Wendy Jenkins (Wageningen University)

Defra Crop Statistics Unit

Judith Murdoch (Efeca)

Published June 2022 by WWF-UK. Any reproduction in full or in part of this publication must mention the title and credit WWF-UK as the copyright owner.

CONTENTS

EXECUTIVE SUMMARY 5

1. INTRODUCTION 19

2. WHAT IS LOW OPPORTUNITY COST LIVESTOCK FEED? 21

'High opportunity cost' feed uses land that could have fed humans directly instead 21

'Low opportunity cost' feed does not compete with direct human nutrition 22

Defining low opportunity cost feed can get complicated 23

Conclusion: a transformative idea 27

3. WHAT DO THE UK'S LIVESTOCK EAT? 29

The UK is home to over 230m livestock animals 30

Grass provides over 75% of the diet for ruminants 31

UK livestock consume 31m tonnes of non-grass feed inputs every year 34

Food surplus and waste - the missing LOC feed? 44

4. ALLOCATING LOW OPPORTUNITY COST FEED 49

The distribution of low opportunity cost feed is uneven across livestock species 49

Ruminants 50

Monogastrics 52

Optimal allocation of LOC feed between species 54

5. COULD A LOW OPPORTUNITY COST SYSTEM FEED THE UK? 55

Livestock fed on LOC feed could produce up to 31g of animal source protein per person per day 55

A LOC feed system in the UK could potentially meet nutritional recommendations 56

6. CONCLUSIONS 59

Lower pressure on land opens up opportunities to bring back nature 60

Research, innovation and policy directions 61

© Jiri Rezac / WWF-UK

THE FUTURE OF FEED:

HOW LOW OPPORTUNITY COST LIVESTOCK FEED COULD SUPPORT A MORE REGENERATIVE UK FOOD SYSTEM

EXECUTIVE SUMMARY

The way we feed our livestock animals places huge burdens on the UK food system and the natural environment. This exploratory report outlines the opportunity to do things differently. If, instead of using land to grow crops for animals to eat, we used these crops to feed humans and prioritised 'low opportunity cost' animal feed sources that do not compete with human nutrition, millions of hectares of arable land could be released for other purposes. By reducing the intense pressure on cropland to produce high yields, land use could be transformed to enable nature to thrive alongside food production in a resilient and resource efficient future.

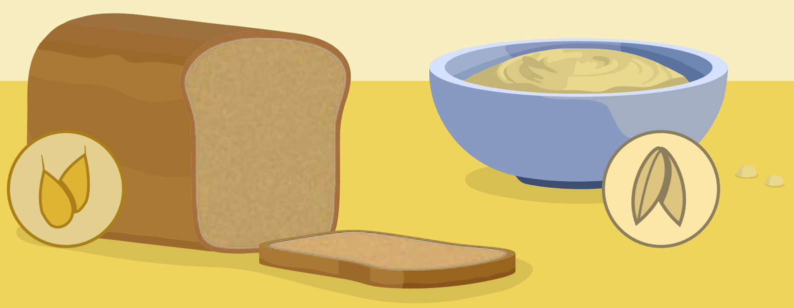
THE WAY WE FEED LIVESTOCK IS INHERENTLY INEFFICIENT

The UK's livestock population in June 2019 stood at 230 million animals, the vast majority of them poultry. Over the course of the year, over 1 billion meat birds were raised and 12 billion eggs were produced. Whilst much of the nutrition for the UK's cattle and sheep is provided by grass, with some supplementation from food industry by-products, fodder crops and grains, our industrially-produced chickens and pigs have a diet consisting primarily of cereal grains and soybean meal. Growing cereal crops to feed animals uses 40% of the UK's entire arable land area - around 2 million hectares - and consumes half of our annual wheat harvest, the nation's most important staple crop.

The land footprint of animal feed is not limited to within our borders.[1] Abroad, an additional 850,000 hectares is used for producing soy cake and meal to feed to livestock in the UK. Most of this soy was grown in South America where it carries a high risk of being associated with deforestation, conversion of non-forest habitats, and biodiversity loss. In addition to land use and land use change, growing crops for animals to eat - in the UK or abroad - is a driver of pesticide and fertiliser use, soil degradation and nitrogen pollution. It is also a substantial contributor to the greenhouse gas emissions associated with producing and consuming animal products - globally, feed represents 75% of the climate impact of poultry production and 60% for pork.

Yet the ecological burden of feeding our livestock is out of proportion to the contribution made by meat, eggs and dairy ('animal source food') to calories and protein in the UK diet. Grazing and crops grown for animal feed combined represent 85% of the nation's total agricultural land footprint - at home and abroad - whilst supplying only 32% of our calories and 48% of our protein. This is because the way in which we currently produce much of our animal source food is inherently inefficient. Using arable land to feed livestock, rather than using it to feed people directly, means that far fewer calories reach the human population than might otherwise be the case. Rather than consuming the products of animal agriculture fed on crops that humans can eat, it would be more efficient, in terms of land use and inputs, for people to consume those crops directly. On one estimate, if all edible crops were consumed by humans instead of some being fed to livestock, enough extra calories would be available to feed an additional 4 billion people globally.

THE OPPORTUNITY COST OF FEEDING THE UK LIVESTOCK POPULATION



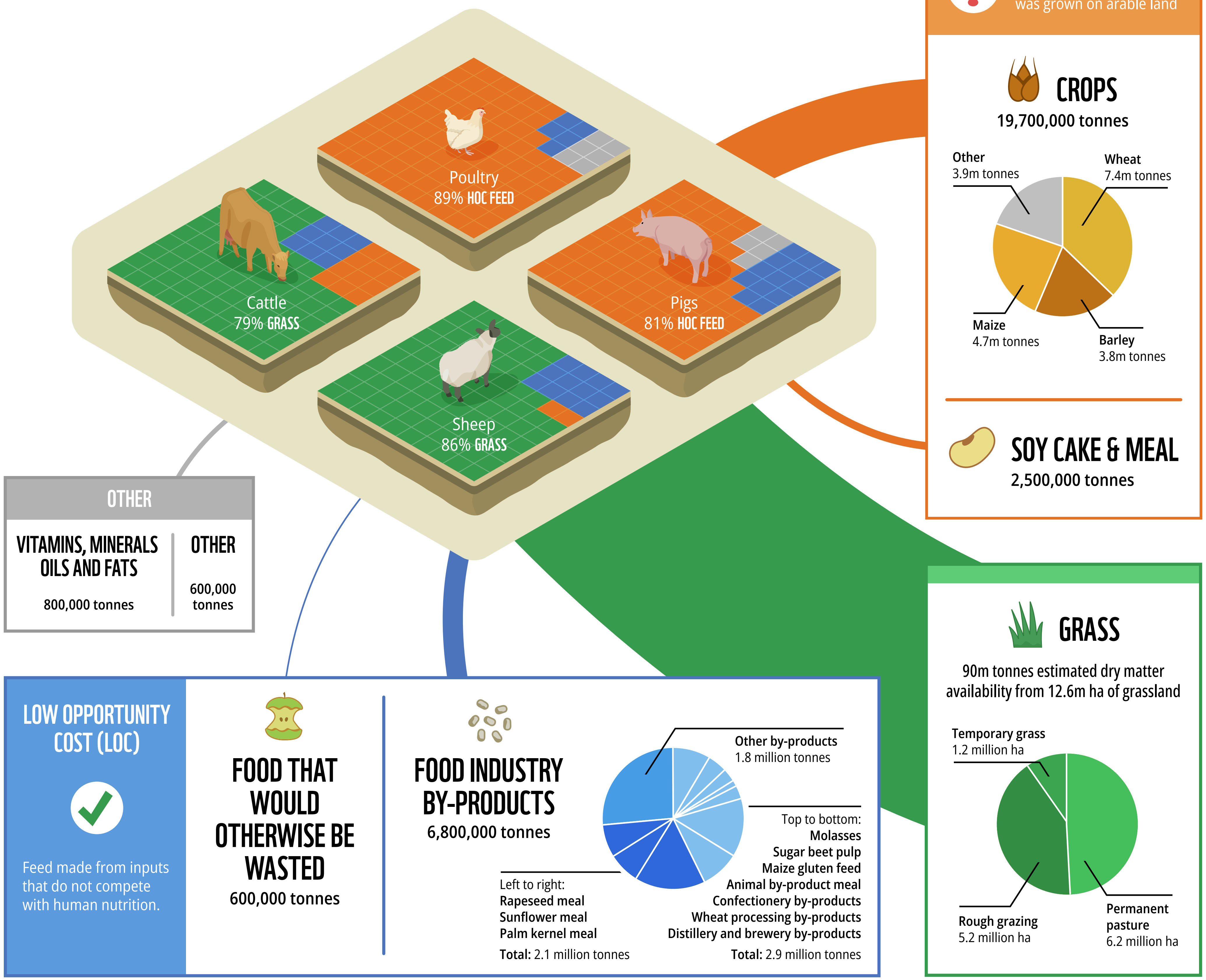
The amount of **wheat** used to feed animals is equivalent to

10.7 BILLION LOAVES OF BREAD

The amount of **oats** used to feed animals is equivalent to

5.8 BILLION BOWLS OF PORRIDGE

HOW WE FEED OUR LIVESTOCK



> **LIVESTOCK HAVE THE POTENTIAL TO PLAY A KEY ROLE IN A REGENERATIVE, AGROECOLOGICAL FOOD SYSTEM**

IF WE FEED LIVESTOCK DIFFERENTLY THEY CAN BE PART OF A SUSTAINABLE FOOD SYSTEM

Despite the inefficiency of feeding animals with edible crops, livestock are not necessarily bad news for the planet. Livestock animals have the potential to be fed without competing with direct human nutrition at all, and in so doing, play a key role in a resource-efficient, regenerative and agroecological food system. This paper explores the idea of feeding livestock using 'low opportunity cost' feedstuffs that are non-competitive with human nutrition. By using resources such as grass, food waste, and food industry or agricultural by-products instead of cereals or soy, more food can be produced overall than in a vegan food system, whilst reducing demand on arable land globally. And ruminants in particular can play an important role in building soil fertility without the need for artificial nitrogen fertilisers - a key opportunity to build a resilient and climate-friendly farming system.

WHAT IS LOW OPPORTUNITY COST LIVESTOCK FEED?

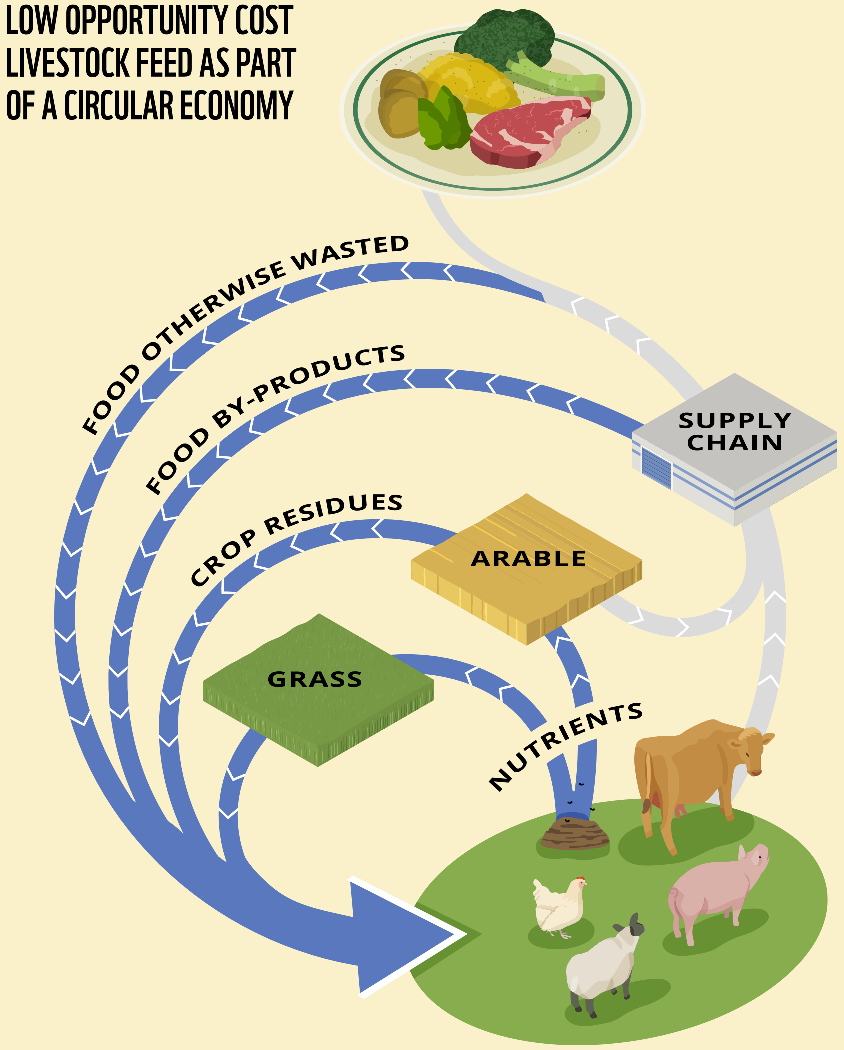
In short, low opportunity cost feed refers to "feed resources unsuitable or undesired for human consumption" - using them does not entail the 'opportunity cost' of forgoing their use as food for people. This includes primarily grass, food industry by-products and food that would otherwise be waste.

"High opportunity cost" feed, by contrast, could have been consumed directly by people, or is grown on land that could have been used to grow food directly for people. For the purposes of this paper, this refers primarily to cereal crops and soy products.

The concept does hold some complexities. For example, soy meal could be considered to be a by-product of crushing soybeans for edible oil. However, in practice, over two thirds of the economic value of the soybean comes from the meal, making animal feed the main driver of production. The same cannot be said of other oilseed meals, where the meal generates a lower proportion of the overall value and is therefore more genuinely a byproduct.

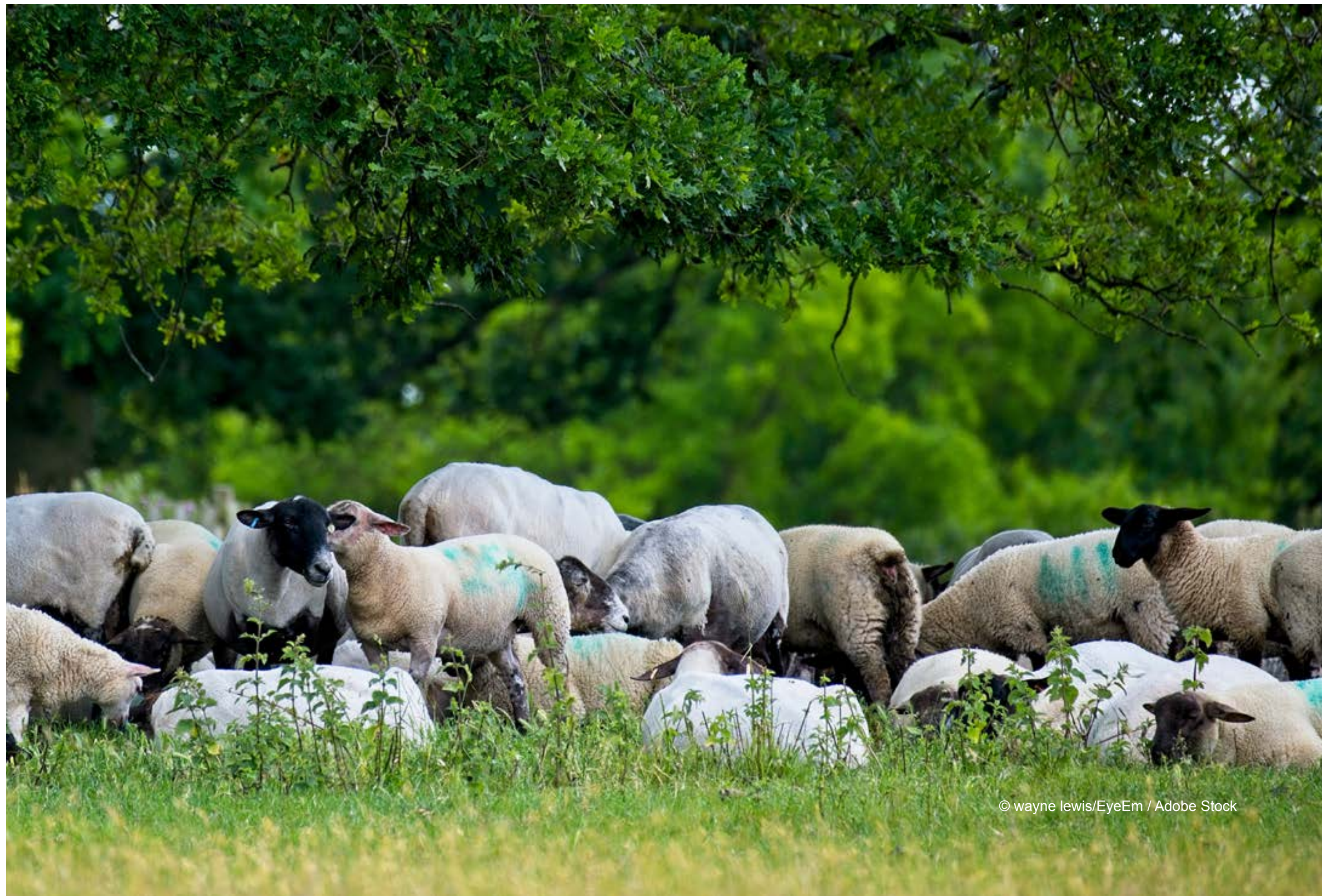
Figure 1

LOW OPPORTUNITY COST LIVESTOCK FEED AS PART OF A CIRCULAR ECONOMY



When grown on land not suitable for arable cropping, or as part of a crop rotation, grass is a low opportunity cost feed source, and flourishes in our climate. Grass can provide high quality nutrition for ruminants for much if not all of the year, either grazed in its fresh state, or consumed as hay or silage. UK grassland is primarily permanent pasture, including both rough grazing land and lowland grazing 'improved' with fertiliser applications to support higher stocking densities. Our national grass resource also includes a smaller area of temporary grass, legume and herb leys, which build soil health as part of crop rotations. Incorporating ruminants alongside temporary grass in an agroecological system can build soil fertility whilst also providing nutritious forage. Overall such systems have the potential to reduce the need for synthetic nitrogen fertilisers in crop production - an essential ambition in tackling climate change and nature loss. Grass is the predominant source of nutrition for most of the UK's cows and sheep, however, there is a trend towards larger farms with more indoor rearing - especially in dairy - which often entails an increase in grain and soy consumption.

Monogastric livestock - pigs and poultry - cannot readily digest grass as a primary food source. However, despite their current diet heavy in soy and cereal grains, pigs are omnivores that traditionally consumed a low opportunity cost diet of food waste and scraps. Even commercial housed poultry, which now generally consume over 90% grains and soy, have been proven on a diet consisting of 100% food industry by-products alongside surplus from food manufacturing and retail that would otherwise go to waste. Whilst the rapid growth and weight gain of hens in intensive poultry systems is underpinned by protein-dense imported feed, poultry can also be incorporated into pasture-based systems, where they are slower growing, and in which up to 25% of concentrate feed can be replaced with foraged foods such as vegetation, seeds, berries, insects and slugs. There is therefore no inherent need for our livestock animals to consume feed that is in competition with direct human consumption.



© Jiri Rezac / WWF-UK

A LIVESTOCK SYSTEM BASED ON LOW OPPORTUNITY COST FEED WOULD LOOK VERY DIFFERENT

> **INSECT MEAL PRODUCED FROM FOOD SURPLUS AND BY-PRODUCTS COULD REDUCE SOY IMPORTS BY 20%**

Livestock production in the UK already entails using some low opportunity cost feed, particularly grass and by-products. But what if high opportunity cost feed ingredients like soy and cereals were excluded entirely? Whilst this may sound like a radical proposition from the current standpoint, it is not unimaginable. Indeed, it is already practised in some farming systems. If this became universal, overall livestock numbers would need to decline due to the reduced availability of feed sources, and the mix of livestock and the availability of different animal source foods would change considerably. First, numbers of poultry would need to be reduced drastically, as low opportunity cost by-product feedstocks suited to the current production paradigm (such as the bakery waste used by Dutch firm Kipster) are limited. In the medium term, legal and technological developments to allow the processing of food waste by insects, producing a high-protein insect meal, could provide an additional feedstock. The first report in WWF UK's Future of Feed series suggests that, with appropriate investment and policy support, insect meal could replace half a million tonnes, or around 20%, of soy in feed by 2050.[2]

Under current rules and systems, the pig population too would need to be reduced. Pigs are well suited to consuming food waste and scraps, but legislation introduced following serious biosecurity breaches and human health hazards including BSE means that this is currently prohibited under most circumstances. Some experts argue, however, that a total ban on food waste is not necessary in order to ensure adequate food safety and contamination standards, and that changes in the law could safely allow some kinds of food waste to be fed to pigs again. This would not be a niche consideration - one academic model has found that appropriate food waste sources could support as much as double the current UK pig population. In Japan, the regulated market for 'eco-feed' allows food waste from catering to be processed through heat treatment, becoming a valuable ingredient in compound feeds for both pigs and poultry.

> **REPLACING GRAINS AND SOY WITH BY-PRODUCTS HAS BEEN SHOWN TO HAVE NO DETRIMENTAL IMPACT ON DAIRY COW MILK YIELDS**

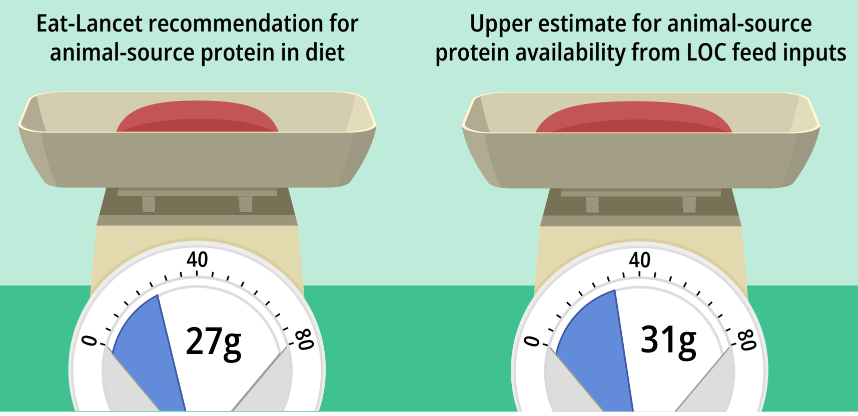
Ruminants, however, are the key to a system based on low opportunity cost feed. Moving away from current trends favouring higher levels of indoor housing and concentrate feed, cows and sheep in a future system would take advantage primarily of the nutrition provided by the UK's permanent and temporary grasslands. This could be done at stocking densities that allow coexistence with biodiversity and healthy soils, and would also boost UK food system resilience in the face of global supply chain disruptions. Suitable breeds would need to be prioritised, and the most efficient approaches would maximise the potential for producing both milk and meat from the same animals. Beyond grass, ruminant diets in a low opportunity cost system could also be supplemented with limited quantities of by-product based feeds such as wheat feed (by-products from milling), molasses, and rapeseed meal, especially at key stages in the life cycle. A number of studies in dairy cows have shown that replacement of cereal or soy inputs with by-products can occur without detrimental impacts on milk yields, despite their notably different nutritional profile.

LOWER LIVESTOCK NUMBERS COULD STILL PROVIDE ENOUGH PROTEIN FOR EVERYONE

All of the low opportunity cost feed sources described in this report are limited in their availability. Food waste, though currently standing at over 9.5m tonnes in the UK annually, must be reduced radically at source to meet over-arching environmental goals - the UN's SDG 12.3 targets a 50% reduction by 2030 - making less available for animals. Following the food waste hierarchy, any edible surplus should also be redirected to human consumption in preference to animals, further reducing the amount available for feed. By-products for use in animal feed are limited to the volumes made available by food manufacturing processes and, if edible, should also be prioritised for human consumption if markets exist. Suitable grassland for livestock is limited by climate and geography and in a future world less reliant on synthetic fertilisers, some current areas of heavily 'improved' pasture would support lower numbers of animals. Grassland availability needs to be constrained further still by imperatives for nature restoration over large areas of land. The UK Committee on Climate Change recommends that 21% of current agricultural land should be prioritised for carbon sequestration - though in many cases, carbon sequestration through nature restoration may not be incompatible with, and may even be enhanced by, livestock grazing at low stocking densities.

> **UK-REARED LIVESTOCK FED ONLY ON LOW OPPORTUNITY COST FEED COULD SUPPLY SUFFICIENT ANIMAL PROTEIN TO MEET NUTRITIONAL GUIDELINES**

This all means that the overall quantity of animal source food produced in the UK under a low opportunity cost feed system would be much lower than currently. Despite this, however, it is striking that an increasing number of academic studies suggest that the amount of meat and dairy produced could be enough to fulfil population nutritional needs at macronutrient level. This is because in the UK we currently consume more calories, protein and animal source foods than recommended. Our protein consumption is 50% higher than national dietary recommendations, and 70% higher than the EAT-Lancet Commission Planetary Health Diet. Furthermore, EAT-Lancet suggests that more than half of protein in the diet on average should come from plant-based sources. If we were to recalibrate our consumption in line with such recommendations, models suggest that UK-reared livestock fed only on low opportunity cost feed could supply sufficient animal protein. The remaining protein requirement would already be met by existing levels of plant-source food consumption, meaning that little if any additional land would be required to produce more plant-based protein. Further research is required to assess the sufficiency of such diets in terms of micronutrients, but at a protein and caloric level, initial studies suggest that a livestock system based on low opportunity cost feed is plausible from a dietary standpoint.



ENVISIONING A DIFFERENT FEED FUTURE

A low opportunity cost feed system in the UK could transform land use, enabling nature to thrive alongside food production, whilst providing sufficient animal source protein for healthy, sustainable diets.

HOW WE FEED OUR LIVESTOCK NOW

The UK's livestock population is highly dependent on imported soy, and cereal crops that could have been consumed by humans

230 MILLION LIVESTOCK ANIMALS

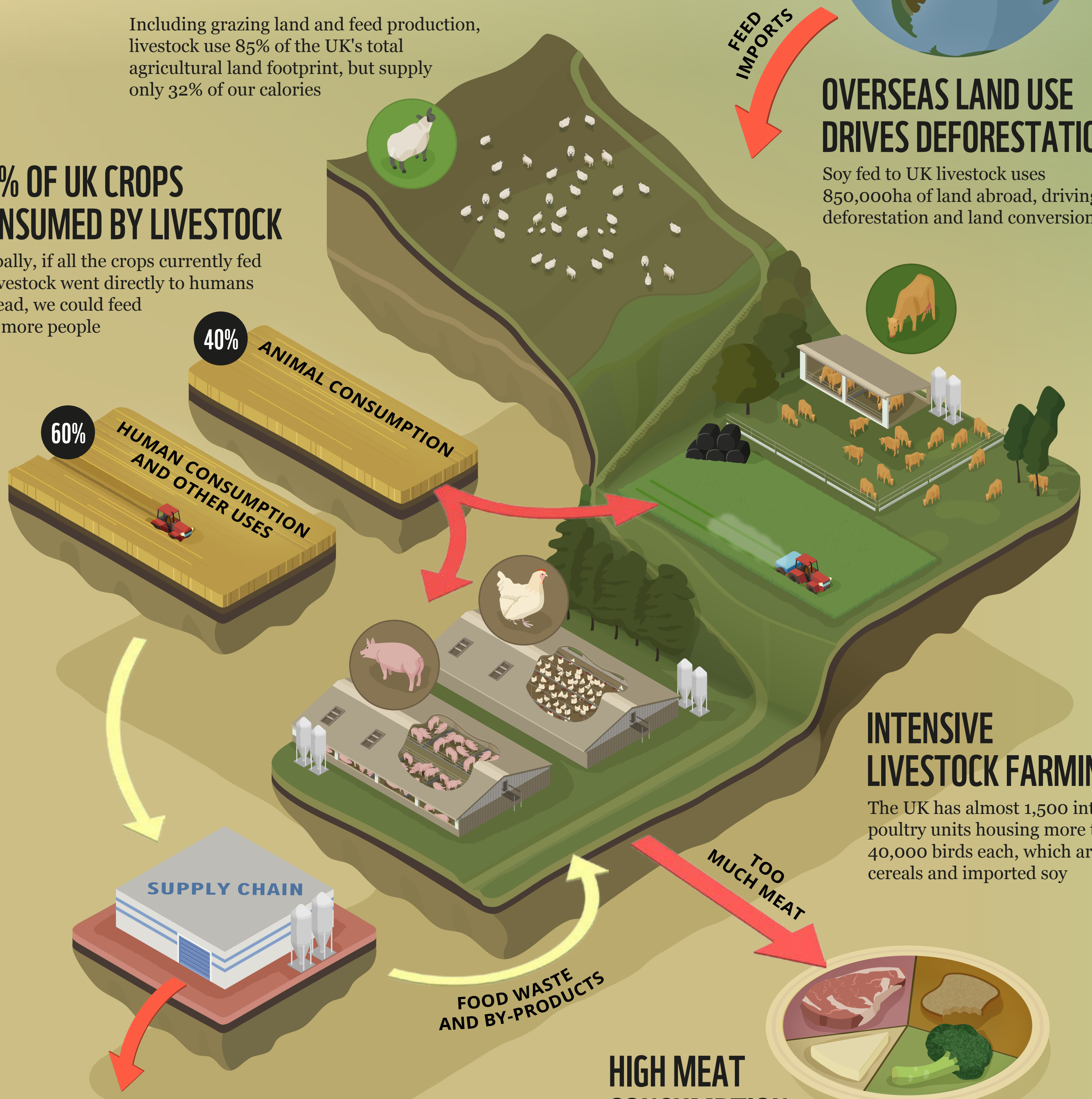
Including grazing land and feed production, livestock use 85% of the UK's total agricultural land footprint, but supply only 32% of our calories

40% OF UK CROPS CONSUMED BY LIVESTOCK

Globally, if all the crops currently fed to livestock went directly to humans instead, we could feed 4bn more people

OVERSEAS LAND USE DRIVES DEFORESTATION

Soy fed to UK livestock uses 850,000ha of land abroad, driving deforestation and land conversion



INTENSIVE LIVESTOCK FARMING

The UK has almost 1,500 intensive poultry units housing more than 40,000 birds each, which are fed on cereals and imported soy

WASTED FOOD

Currently the majority of food waste and surplus is not retained within the food system

HIGH MEAT CONSUMPTION

We over-consume calories and protein and have a diet heavy in animal products

A LOW OPPORTUNITY COST FEED SYSTEM

Feeding our livestock with only grass, food industry by-products, and food that would otherwise be wasted

A SIGNIFICANTLY REDUCED LIVESTOCK POPULATION

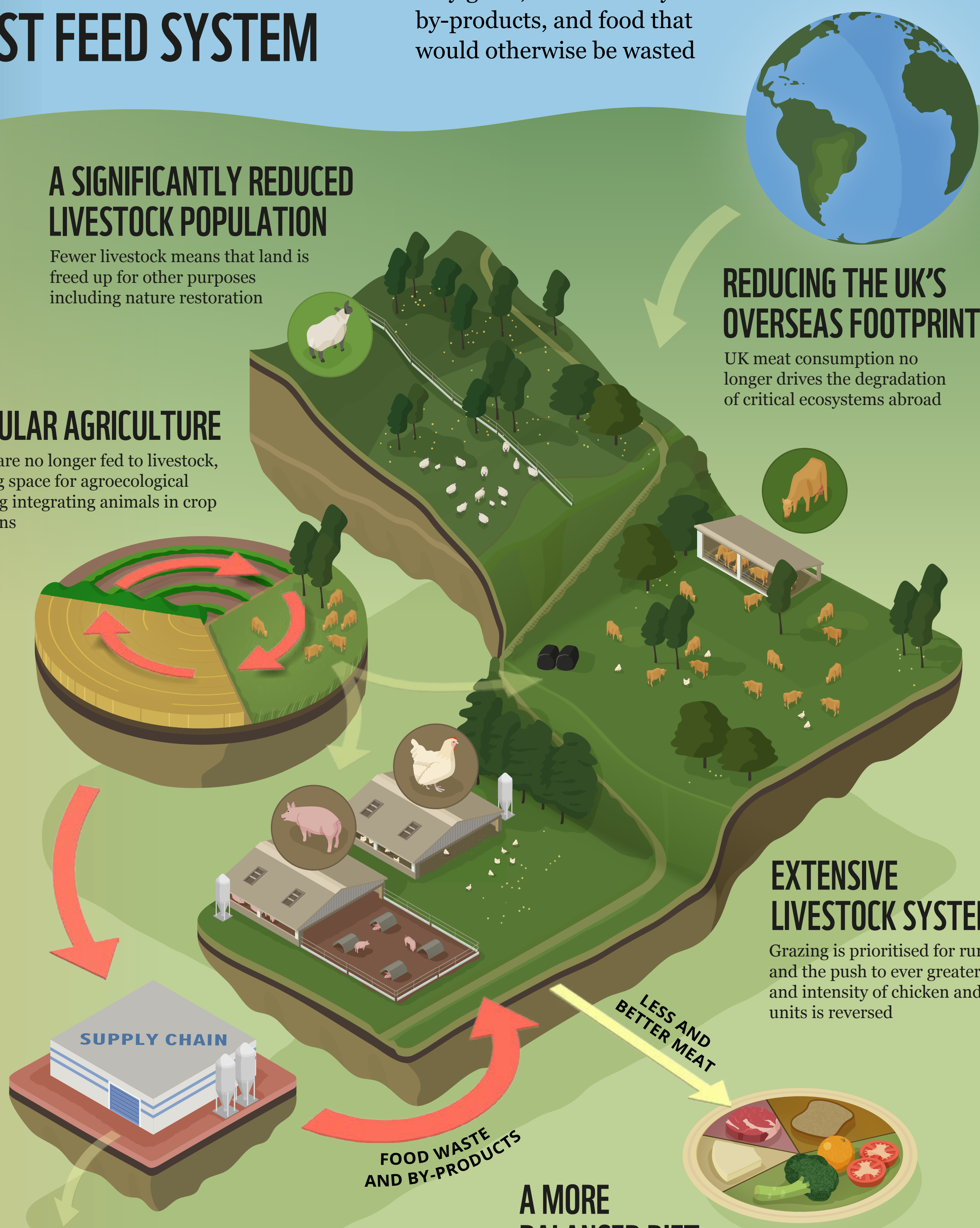
Fewer livestock means that land is freed up for other purposes including nature restoration

REDUCING THE UK'S OVERSEAS FOOTPRINT

UK meat consumption no longer drives the degradation of critical ecosystems abroad

CIRCULAR AGRICULTURE

Crops are no longer fed to livestock, making space for agroecological farming integrating animals in crop rotations



EXTENSIVE LIVESTOCK SYSTEMS

Grazing is prioritised for ruminants, and the push to ever greater size and intensity of chicken and pig units is reversed

A MORE BALANCED DIET

A reduced livestock population fed on low opportunity cost inputs could supply sufficient animal protein to meet nutritional recommendations

THE IMPLICATIONS FOR NATURE COULD BE TRANSFORMATIONAL

Changing the way we think about livestock feed by phasing out grains and soy and prioritising grassland and circular economy inputs such as waste and by-products would have huge implications for nature. Critically, releasing the 40% of arable land in the UK currently producing animal feed (2m ha - around the size of Wales) for other purposes could enable a 'land-sharing' approach to farming, with regenerative agriculture at its heart. This extra slack in the system would allow for a landscape in which an interconnected patchwork of crops, livestock and nature are designed for people, biodiversity and resilience rather than maximum yield per hectare. This will be critical for achieving both carbon sequestration and biodiversity conservation in the UK, one of the most nature-depleted countries in the world. In this future, nature and productive activities go hand in hand, with both supporting farmer livelihoods and rural communities.

An agroecological farming system in the UK would be one in which grazing livestock - albeit in smaller numbers - are at the centre, and integrated with arable cropping systems. Ruminants would play a key role in soil fertility and landscape management, spending the bulk of the year outside. There would be a far smaller role for year-round indoor-housed livestock fed on concentrate and compound feed, reducing nitrogen pollution from manure management and feed. The new feed paradigm would also see a move away from the intensive poultry and pig farming that now predominates in the UK, with 7 out of 10 of the UK's largest poultry farms housing more than 1m birds, and pig farms housing up to 23,000 animals. These systems are optimised for rapid growth and high outputs, but low opportunity cost feed sources would provide neither the volume nor the highly calibrated and protein-dense nutritional inputs that they depend on, necessitating a move towards lower intensity systems. This would help to address the nitrogen pollution and associated damage to aquatic ecosystems linked to intensive indoor animal rearing, as well as responding to concerns around animal welfare.

“ MOVING TO A LOW OPPORTUNITY COST FEED SYSTEM WOULD ALLOW FOR A LANDSCAPE DESIGNED FOR PEOPLE, BIODIVERSITY AND RESILIENCE

Benefits for nature would go beyond the UK. Removing our reliance on imported soymeal would ease the pressure on 850,000 ha of land abroad producing soy primarily for UK animal feed. Farming of soy in South America is a major cause of deforestation and land conversion, a prime driver of biodiversity loss and the major contributor to emissions of 4.5 Mt CO_2e annually. Overall, reductions in deforestation, reductions in land area for arable crops, and reductions in overall livestock animal numbers would result in lower greenhouse gas emissions, directly addressing the 14.5% of global emissions caused by livestock.

“ FEEDING INCREASING AMOUNTS OF CEREAL CROPS AND SOY INTO INTENSIVE PRODUCTION SYSTEMS HAS DEPLETED NATURAL CAPITAL AND MADE LITTLE TANGIBLE DIFFERENCE TO FARMER LIVELIHOODS

ENVISIONING A DIFFERENT FEED FUTURE

Feeding livestock only on low opportunity cost inputs would be a sweeping departure from the direction of travel for livestock feed over the last 50 years, which has incorporated increasing quantities of cereal crops and soy into ever more specialised and intensive production systems. There are barriers to challenging the status quo. Even as it has depleted natural capital and made little tangible difference to farmer livelihoods, the current way of feeding livestock has developed because it has made economic sense within a system that fails to internalise environmental impacts. High opportunity cost feed provides concentrated and efficient nutrition delivered through international commodity markets and a network of specialist companies, resulting in high feed conversion ratios and cheap meat. Low opportunity cost feed sources such as food waste are more nutritionally variable, and less easily traded, transported, blended and stored. More work is required to discern the extent to which low opportunity cost feeds could become a viable replacement for grains and soy in a future in which the UK has fewer livestock animals, and animal-source food has a less central place in our diet. Such a system would certainly require the prioritisation of different animal breeds, and different expectations around yields of meat and milk per animal. However, existing 100% pasture-fed livestock systems show that this can be commercially viable and indeed that on upland and marginal farms, focusing on naturally available grass can increase profitability.

The prioritisation of ruminants does raise important questions around greenhouse gas mitigation pathways, as on a per gram of protein basis, ruminant animals produce the most greenhouse gas intensive meat, whilst chicken is the least intensive. This is particularly pertinent given current debates around the role of methane in climate change. However, a mono-dimensional view of cost-benefit through the lens of immediate greenhouse gas emissions alone fails to factor in the wider systemic benefits of maintaining a relatively small number of ruminant animals in a mixed agroecological farming system, and overlooks the disbenefits of large-scale intensive poultry farming in terms of land use for feed, air and water pollution, and animal welfare. There is therefore a need to develop new and more systemic ways of assessing overall impacts. Also requiring a systemic approach would be very practical economic questions around the role of trade in a future where the UK decided to prioritise low opportunity cost feed. While this paper looks at the UK as a semi-closed system on the basis of our current high levels of self-sufficiency for animal source food products, any future policy directions in this area would need to avoid the risk of offshoring environmental impacts by replacing or supplementing UK meat and dairy with imported food produced under lower environmental standards.

While many questions remain, what is clear from this report is the huge potential benefit that could come from significantly decreasing cereals and soy in livestock feed and prioritising animal nutrition from low opportunity cost sources. Such a move would not be starting from zero - low opportunity cost feed sources including grass and by-products already represent a significant proportion of animal nutrition in the UK, and with innovation and investment have huge potential to achieve further scale. With its implications for a greatly reduced livestock population, lower meat and dairy consumption and resource efficiency, this approach is in line with a range of vital sustainability imperatives to reach net zero carbon and halt biodiversity loss. In a world where the majority of our protein came from plant-based food, an integrated agro-ecological livestock system using grass, waste and by-products as the main feed inputs could provide enough animal protein for everyone whilst facilitating the huge changes in land use, improvements in biodiversity, and reduction in greenhouse gas emissions that are needed to ensure the sustainability of human life on earth.

RESEARCH, INNOVATION AND POLICY DIRECTIONS

This report has six recommendations for increasing the proportion of animal feed from low opportunity cost sources:

1 BE CLEAR ON THE NEED FOR 'LESS AND BETTER' MEAT AND DAIRY IN THE UK

Despite overwhelming evidence that reducing meat consumption in western economies is essential for achieving sustainability goals including climate change, this is still not reflected in the UK's official net zero strategy. It is vital to keep making the argument, emphasised in WWF's Livewell reports,[3] that rebalancing the UK's average dinner plate substantially in favour of plants, and reducing all meat, not just red meat, will be needed to ensure a sustainable, healthy future. This can be accomplished at the same time as prioritising 'better' production systems that value nature, animal welfare, and farmer livelihoods. Food businesses and government have a key responsibility to provide farmers with the economic and policy support that will enable a just transition to a 'less and better' system to occur.

2 NORMALISE A MULTI-METRIC APPROACH TO SUSTAINABLE FOOD POLICY

In the urgent drive to tackle climate change there is a risk that food policy is made on the basis of one-dimensional greenhouse gas metrics. For instance, some dietary sustainability recommendations prioritise poultry meat consumption because of its low greenhouse gas emissions per gram of protein. The low opportunity cost feed framework turns this on its head, highlighting the pressures that intensively-produced poultry places on the environment locally and globally. An opportunity cost lens on sustainability shows that it is essential that food policy takes a systemic, multi-metric approach including land, water and biodiversity, not just greenhouse gas emissions.

3 BRING LOW OPPORTUNITY COST FEED INTO MAINSTREAM POLICY DISCUSSION AND CORPORATE TARGETS

Ideas around low opportunity cost feed are currently largely absent from government and corporate narratives around food sustainability, especially given the growing dominance of the net zero discourse and associated action frames. However, moving towards such a system could be an important part of building a sustainable and resilient food sector, reducing reliance on global commodity markets and artificial fertilisers, and building instead on the skills and knowledge of farmers to deliver regenerative agricultural solutions. This could be encouraged through incentives such as Environmental Land Management Schemes (ELMS), which could promote agroecological practices such as the inclusion of grass and livestock in arable rotations. There is a need for advocacy to push low opportunity cost feed into government policy and corporate strategy discussions and targets, spurring innovation and opening up new possibilities for action.

4 PROMOTE INNOVATION IN LOW OPPORTUNITY COST FEED

Technological innovations already under development offer multiple opportunities that could transform the availability and utilisation of low opportunity cost feed inputs to the livestock sector, and accelerate a transition away from cereals and soy for monogastric animals as well as ruminants. These include insect-rearing, microbial proteins from fermentation, seaweed, and biorefinery, alongside others. With adequate investment and government support including enabling policy, research funding and subsidies, these kinds of technologies are potentially scalable to represent a substantial contribution to high-protein, low opportunity cost animal feed. Businesses should seize the opportunity for innovation and work with supply chain actors to share costs and promote R&D.

5 FUND UK-SPECIFIC DATA, RESEARCH AND MODELLING

There is currently very little UK-specific research and modelling on what a livestock system based on low opportunity cost feed could look like. This is needed to test whether the assumptions of EU and global models hold true. There are also significant gaps in official Defra data relating to the UK's current livestock feed inputs and these need to be filled in order to provide a complete picture. Far greater transparency and traceability around feed inputs is required - not just for compound feeds but across the board. Attention is also needed to drive practical, on-farm research around business models, practices and the nutritional optimisation of low opportunity cost feeds.

6 REVIEW CURRENT REGULATIONS ON THE USE OF FOOD WASTE IN ANIMAL FEED

Reducing the production of food waste needs to remain the policy priority. The experiences of other countries, coupled with new technologies, offer the potential that food waste could safely become a source of low environmental impact feed - both directly, for pigs, and indirectly, via insects. Whilst the disease transmission risks from poor practice are real, it is plausible that control measures could provide appropriate safeguards. The EU has already softened some regulations around food waste as a feed source - the Food Standards Agency should now be mandated to research whether a partial reintroduction of food waste as a feed source could be feasible.

END OF EXECUTIVE SUMMARY
SEE OVERLEAF FOR CHAPTER ONE

© Joseph Gray / WWF-UK

CHAPTER 1 > INTRODUCTION

> LIVESTOCK USE 40% OF THE WORLD'S HABITABLE LAND AREA AND PRODUCE 14.5% OF ALL ANTHROPOGENIC GREENHOUSE GAS EMISSIONS

> GRAINS FOR LIVESTOCK USE UP TO A THIRD OF THE ANNUAL GLOBAL CEREAL HARVEST

There is increasing scientific and policy recognition that changes to meat and dairy consumption and production will play a vital part in meeting the goals of reducing humanity's global footprint, limiting global warming to 1.5°C, reversing global biodiversity loss by 2030 and feeding a growing population within planetary boundaries.[4] The scale of the challenge is enormous - combined together, grazing by ruminant animals and the production of other livestock feed inputs use up to 40% of the world's habitable land area.[5] Livestock contribute 14.5% of all anthropogenic greenhouse gas emissions and are a significant contributor to water and air pollution, soil acidification and biodiversity loss.[6] In the UK, livestock and their feed represent 85% of the nation's total land use for agriculture - including our overseas land footprint - whilst supplying only 32% of our calories and 48% of our protein.[7] Lowering livestock's burden on the earth by switching to a greater reliance on plant-based nutrition would have significant implications for environmental sustainability.

It is now clear that a swift decline in the high levels of consumption of meat and dairy in countries like the UK needs to be a priority, for health as well as environmental reasons. However, changes in production - how animals are reared and what they eat - are also an important part of the picture. Feed represents 75% of the global warming impact of poultry globally, 60% for pork, and 33% for dairy production.[8] Grains for livestock use up to a third of the annual global cereal harvest, taking up land that could have been producing food directly for human consumption.[9] However, it is also the case that across the world, as well as cereal grains, livestock depend significantly on so-called 'low opportunity cost' nutritional inputs that people cannot or will not consume, like grass, crop residues, by-products from food processing, and food waste and surplus. Prioritising these feed sources that use less land and produce lower greenhouse gas emissions could have a big role to play in achieving environmental goals.

WHAT IS LOW OPPORTUNITY COST (LOC) FEED?

OPPORTUNITY COST

"the potential benefits that are missed out on when choosing one alternative over another"

LOW OPPORTUNITY COST LIVESTOCK FEED

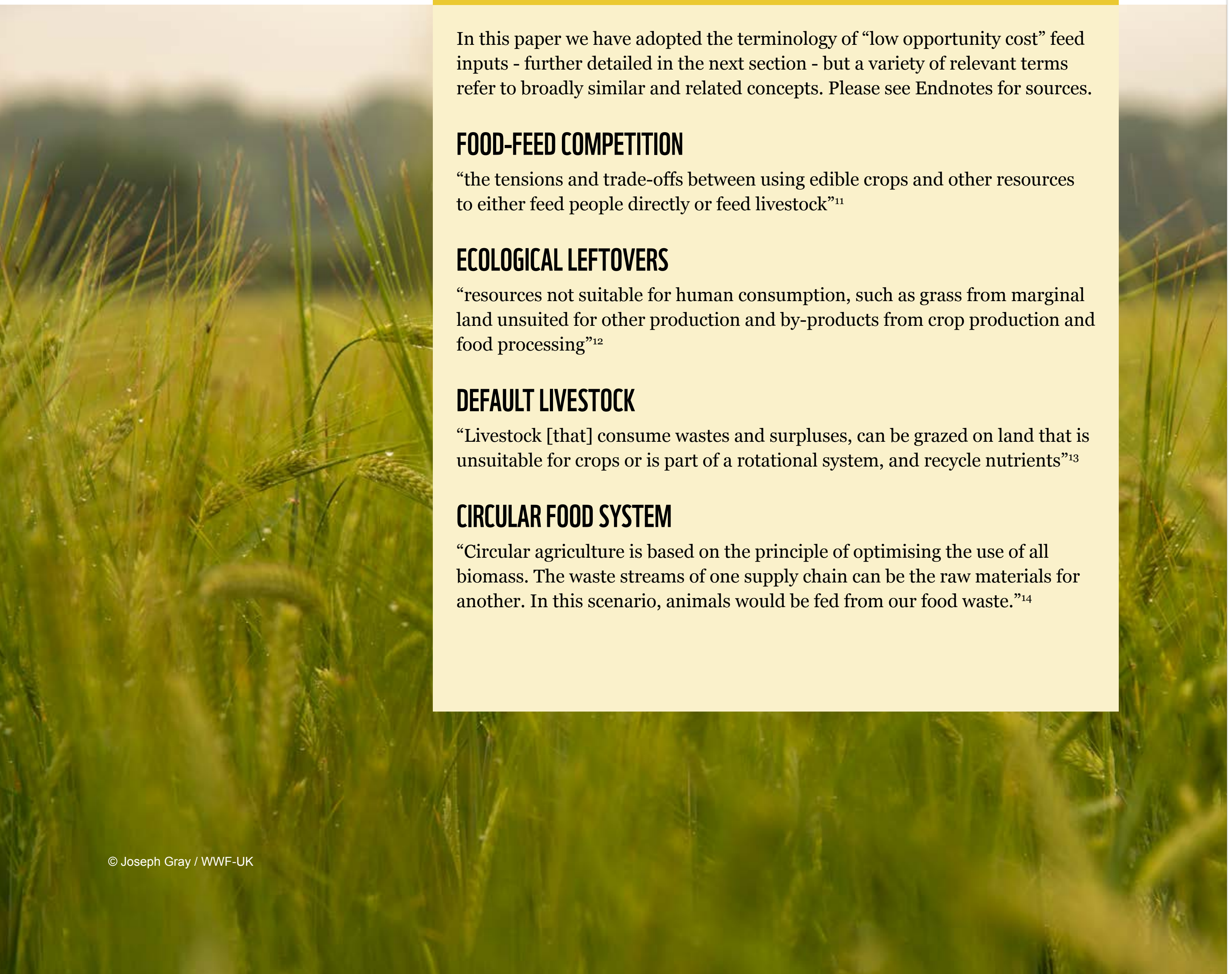
"feed resources unsuitable or undesired for human consumption"[10]

Opportunity cost in this context is a shorthand that refers in practice to the loss of one specific alternative opportunity: the ability to feed people directly. For example, when land is used to grow cereal crops for animal feed, the foregone opportunity referred to is the consumption of those crops by people, or the use of the same land to grow other crops for direct consumption. Low opportunity cost refers to the absence of this competition between food and feed.

It is important to note that the production of plant-based food is not the only alternative opportunity for using land currently growing feed for animals. Land could also be used for nature restoration or the production of renewable energy, for example. And neither are potential 'low opportunity cost' feedstocks themselves free of alternative uses. Instead of feeding animals, crop residues could mulch and enrich soil, and food waste could be turned into energy and compost. Some of these issues are discussed throughout the paper.

Fundamentally re-thinking livestock systems to privilege low opportunity cost (LOC) inputs to animal nutrition - and exclude crops like grains and soy that drive land use and habitat conversion globally - would do much to limit the current impacts of livestock production. It would also place a natural limit on the level of livestock production and consumption that could be sustained globally, since LOC inputs like by-products and suitable grassland are inherently limited, and would support considerably lower livestock numbers than a system with heavy reliance on crops. Alongside limiting livestock numbers and animal source protein overall, a system based on LOC feed would have big implications for the types of livestock that we produce, with a far more limited role for monogastric species (especially poultry) that do not have the ability to digest grass.

This paper aims to explore what prioritising low opportunity cost feed in UK animal agriculture might mean for both production and consumption. The following sections look at the key parameters and caveats around the low opportunity cost idea; the current feed system underpinning livestock production in the UK; how much of current feed is composed of low opportunity cost inputs; and the potential implications of maximising low opportunity cost feed for UK agriculture, human nutrition, land use and the environment.



A GUIDE TO TERMINOLOGY

In this paper we have adopted the terminology of "low opportunity cost" feed inputs - further detailed in the next section - but a variety of relevant terms refer to broadly similar and related concepts. Please see Endnotes for sources.

FOOD-FEED COMPETITION

"the tensions and trade-offs between using edible crops and other resources to either feed people directly or feed livestock"[11]

ECOLOGICAL LEFTOVERS

"resources not suitable for human consumption, such as grass from marginal land unsuited for other production and by-products from crop production and food processing"[12]

DEFAULT LIVESTOCK

"Livestock [that] consume wastes and surpluses, can be grazed on land that is unsuitable for crops or is part of a rotational system, and recycle nutrients"[13]

CIRCULAR FOOD SYSTEM

"Circular agriculture is based on the principle of optimising the use of all biomass. The waste streams of one supply chain can be the raw materials for another. In this scenario, animals would be fed from our food waste."[14]

CHAPTER 2 > WHAT IS LOW OPPORTUNITY COST LIVESTOCK FEED?

2.1 'HIGH OPPORTUNITY COST' FEED USES LAND THAT COULD HAVE FED HUMANS DIRECTLY INSTEAD

HIGH OPPORTUNITY COST

feedstuffs that could have been eaten by people directly, or were grown on land that could have been used to grow crops to feed people directly.

At the heart of the idea of low opportunity cost feed is the concept of 'food-feed competition' - the tension between using land directly to grow crops to feed humans, and using it to feed livestock. The core argument is that on a purely calorific basis, using crops for feed that could have been consumed directly by humans is an inefficient use of limited resources, as by necessity, animals must consume more calories than they provide through the resulting animal source products. Many of the calories in the consumed feed are used in metabolism and growth, incorporated into inedible body parts, or lost as faeces or urine.[15] It would therefore be more efficient for us to use land to grow crops that go directly to feed people.[16] This would result in more food being available globally, lower demand for inputs and lower pressure on natural habitats and freshwater. On one estimate, if all edible crops were consumed by humans instead of some being consumed by livestock, enough extra calories would be available to feed an additional 4 billion people globally.[17]

While there are evidently caveats to this argument, it does contain important insights, especially in the context of large-scale industrialised food systems. The case is most clearly made around cereal crops, with 36% of the world's harvest fed to animals rather than humans.[18] It is estimated that the same harvest could provide around six times as many calories if eaten directly by humans.[19] A similar point can be made about agricultural land that could be used to grow crops for human consumption but is instead used to grow feed crops that are not generally part of the human diet. Some of the 'grain crops' in the above statistic may indeed fall into this category, such as maize varieties grown for silage. Soy needs to be thought of slightly differently, as whilst soy oil for human consumption is one of the products of soya bean production, soy meal for animal feed is actually a more significant driver of value and land use. Soy in feed would therefore be classified as high opportunity cost as the land it is grown on could be used primarily for producing food, rather than, as currently, feed. This is further discussed below.

"IT IS ESTIMATED THAT THE SAME HARVEST COULD PROVIDE AROUND SIX TIMES AS MANY CALORIES IF EATEN DIRECTLY BY HUMANS

2.2 'LOW OPPORTUNITY COST' FEED DOES NOT COMPETE WITH DIRECT HUMAN NUTRITION

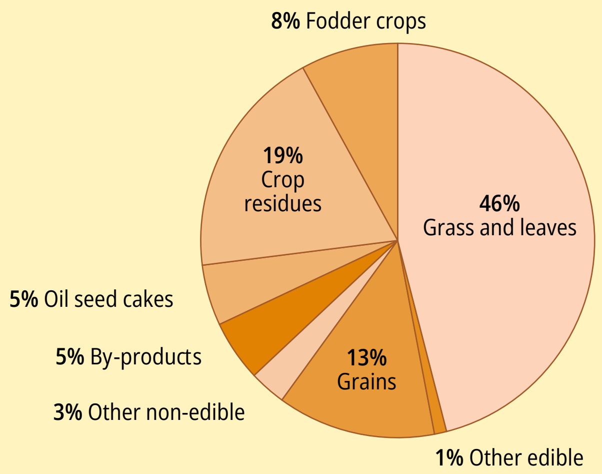
LOW OPPORTUNITY COST

feedstuffs that are inedible or undesired by people; were not grown on land that could have been used to grow crops to feed people directly; feedstuffs derived from by-products or waste.

Despite the huge amount of land used worldwide to produce animal feed, high opportunity cost inputs like grains, fodder crops and soy represent only around one quarter of feed globally (see Figure 2).[20] The majority of the remainder consists of inputs that do not compete with direct human nutrition, including grass and leaves (46%), crop residues such as straw (19%) and food industry by-products (5%). Livestock are well adapted to utilise these low opportunity cost resources, in particular grass - and this is indeed the evolutionary origin of the ruminant digestive system. Pigs and poultry, meanwhile, have historically eaten scraps and waste, and innovations in the Netherlands show that poultry and egg production using solely by-product feeds can be achieved on a commercial level.[21]

Figure 2
GLOBAL LIVESTOCK FEED RATION COMPOSITION

GLOBALLY AROUND THREE-QUARTERS OF LIVESTOCK NUTRITION IS PROVIDED BY LOW OPPORTUNITY COST INPUTS



ELIMINATING ALL FEED PRODUCED ON ARABLE LAND GLOBALLY COULD FREE UP 560 MILLION HECTARES, AN AREA HALF THE SIZE OF EUROPE

Given that livestock can be reared without high opportunity cost inputs, the question is then whether such a regime would be feasible or desirable on a large scale, which is explored more fully in the rest of the paper. If it were achieved, eliminating all feed produced on arable land globally could free up 560 million hectares.[22] This would imply hard limits on the number of livestock animals that could be supported under such a system due to the lower availability of animal nutrition - and therefore limits on the production of animal-source foods. At least some, but not all, of the freed up land would therefore need to be used to produce additional crops for human consumption under a more plant-based diet than today.

Compared to a vegan diet, however, less arable land would be required overall because of the nutritional contribution of the remaining livestock.[23] In a circular food system, these limited numbers of livestock would also play a key role in improving soil fertility through manure, and contributing to landscape management and conservation through managed grazing. Given the considerably higher efficiency of producing calories for humans through crops directly rather than with the intermediation of animals, the same agricultural land area would be called upon to produce significantly less food overall. This would cut through debates around land sparing and sharing, making lower yielding, nature-friendly farming more possible. It would also potentially release areas of land for alternative purposes such as the production of renewable energy, carbon sequestration, and nature restoration.

2.3 DEFINING LOW OPPORTUNITY COST FEED CAN GET COMPLICATED

Whilst the idea that human edible food should be eaten directly by humans is compellingly simple in theory, in practice the low opportunity cost concept presents a more complex web of questions than it might first appear.

Table 1 **KEY ISSUES IN DEFINING LOW OPPORTUNITY COST FEEDSTUFFS**

GRASS

Should grazing land that is suitable for cropping be converted to arable?

Should poor quality arable land be converted to grazing?

What is the role of temporary grass as part of an agroecological system?

NATURE RESTORATION

Should grazing land be used for nature restoration?

Could lower intensity grazing produce better biodiversity and environmental outcomes?

GREENHOUSE GAS EMISSIONS

How do we weigh up higher methane emissions from consuming grass vs. the impacts of more digestible high opportunity cost feed?

GRAINS

Are quality grading standards too stringent, excluding edible food from being directly consumed by people?

How much overproduction is necessary to protect food security?

AGRICULTURAL BY-PRODUCTS (E.G. STALKS AND STOVER)

Are these by-products of a potentially unsustainable land-use e.g. biofuel production?

Should they be left on the land to increase soil fertility?

MANUFACTURING BY-PRODUCTS

Are by-products actually edible and nutritionally valuable?

Is generation of the by-product avoidable e.g. in less refined versions of the product?

FOOD SURPLUS AND WASTE

Is food surplus and waste genuinely unavoidable, or is it the result of an inefficient food system?

Could surplus have been consumed by people?

SOY, OIL PALM AND OILSEEDS

Is the feedstuff a driver of land use and land use change, or is it genuinely a low-value incidental by-product?

Is the system generating the by-product high risk for deforestation or other environmental impacts e.g. oil palm production?

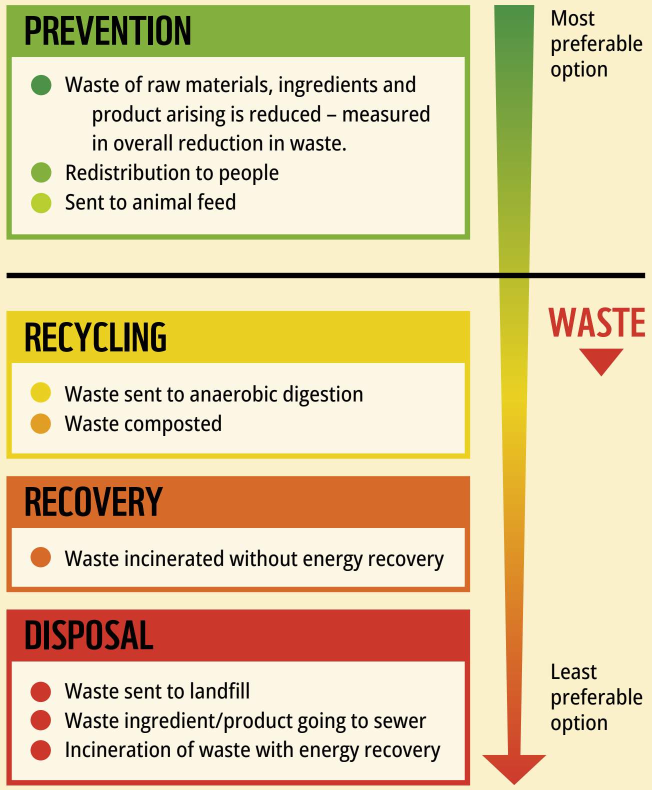
WHAT DOES EDIBLE REALLY MEAN?

For instance, one of the core assumptions within the LOC feed idea is that all potential feedstocks that are actually edible by humans are high opportunity cost. However, what is considered 'edible' is a fungible concept. For example, a significant proportion of cereals currently used in animal feed are grade-outs that do not meet supply chain quality grading standards. This includes, for example, wheat that does not have a high enough proportion of protein to meet the demands of bread manufacturers. These standards are to some degree subjective - low protein content does not necessarily mean that wheat cannot be used to make bread, just that there is not sufficient market demand for this kind of wheat. So whilst these grains may be technically edible in theory, they are not part of an economic system that would render them edible in practice through processing. Such low quality crops need to be differentiated from crops that are ruined or damaged and cannot be consumed - for example, grains that are contaminated by mould - but these are also unlikely to be suitable for consumption by animals. The same analogy applies to misshapen fruit and vegetables that are considered unfit for retail despite being edible. LOC feed policies would therefore need to work to increase market demand for lower quality cereals before advocating for their exclusion from the animal feed supply chain, in order to avoid perverse consequences.

WHAT IS WASTE?

'Waste' is to some degree a culturally and economically defined concept - and includes food that we do not want to eat or is not economically beneficial to channel into the human food supply chain. It can also be argued that a degree of over-production of basic cereals is necessary to protect global food security in the face of supply chain shocks - with the implication that we must accept that some cereals in high production years are not used for human consumption.[24] Overall though, a critical concern in thinking through the low opportunity cost feed concept is to promote policies that make all efforts to direct edible food towards human consumption first, prior to it becoming animal feed. In the current inefficient global food system, up to one third of all food is wasted. Whilst this wastage represents a potential source of 'low opportunity cost' animal feed relative to other destinations such as anaerobic digestion, incineration or other destinations (see the food waste hierarchy, Figure 3), it is 'high opportunity cost' relative to being consumed by people. In an optimised system, wastage should be reduced as far as possible to that which is genuinely unavoidable.

Figure 3 **FOOD WASTE HIERARCHY**



Source: WRAP 2018, Food waste measurement principles and resources guide

ARE BY-PRODUCTS ALWAYS LOW OPPORTUNITY COST?

Some by-product sources of feed present related issues. For example, wheat bran (a by-product of flour refining) is technically edible but the existing market for it is smaller than the supply. While arguably it would be more calorically efficient and health promoting to incorporate greater quantities of wheat bran in human diets, excluding wheat bran from animal feed now would result in wastage or lower grade uses such as biomass for energy, unless measures to promote human consumption were also put in place. Agricultural by-products like stalks can be fed to animals - but should they be left on the land to enrich soil fertility? Other by-products, like rapeseed meal and sunflower meal, which are the relatively low-value non-edible solid residues from the extraction of oils, can be considered to be low opportunity cost. Even in the case of oilseed by-products, however, there may be question marks. For example, the pressing of palm kernel oil results in a solid residue by-product called palm kernel expeller (PKE), which is often incorporated into ruminant diets. Whilst clearly a by-product in terms of not being the main driver of oil palm production, its existence depends on practices that drive deforestation. Arguably a sustainable livestock feed system should not be built on the by-products of unsustainable practices, so some might argue that PKE should not be considered low opportunity cost unless it can be guaranteed to be from a traceable deforestation-free source.

BY-PRODUCT OR CO-PRODUCT?

'By-products' are defined as secondary or incidental products arising during the processing and manufacture of other products, for example spent grains produced during brewing or distilling, and by-products of milk production (e.g. whey). A number of these products are commonly used in animal feed in the UK[25].

There is no standard definition for 'co-product' but it is often used to describe materials being produced during food processing or manufacture that are not the primary product but which are, or can be, transformed into other useful products suitable for human consumption or of relatively high economic value.[26]

The distinction between by-products and co-products can be complicated as there is no standard definition to determine when a by-product becomes useful or valuable enough to be considered a co-product. Sometimes the choice will be made based on a rhetorical rather than definitional basis. In this paper we have chosen for simplicity to refer primarily to by-products and primary products.

WHY SOY MEAL IS NOT A BY-PRODUCT

A far clearer case can be made against soy meal, one of the world's most important animal feed ingredients. Whilst sunflower, rapeseed and palm kernel meal all represent only a small fraction of the overall value of the oil-pressing process that they originate from, in the case of soy around two thirds of the overall value of crushed soybeans is derived from the meal, which is predominantly used for animal feed.[27] In this case therefore, soy meal should be considered to be high opportunity cost as it is in itself a primary driver of land use and land conversion.[28] Some frameworks suggest that if a co-product contributes over ⅔ of overall economic value it should be considered the main driver of production. It is worth noting, however, that lower value by-products and co-products do often still make a non-negligible contribution to overall economic value, and in these cases do contribute to driving any negative impacts associated with specific value chains, even if they are not the main driver. They do not therefore represent 'no opportunity cost' or zero impact even if they are 'low opportunity cost'.

Soy meal is considered to be high opportunity cost as it in itself is a primary driver of land use and habitat conversion.

© Peter Caton / WWF-UK

SOME GRASSLAND COULD THEORETICALLY BE USED FOR PRODUCING CROPS

Issues around land represent another category of tricky challenges in defining low opportunity cost feed. Whilst grass itself cannot be eaten by humans, it may be grown on land that could otherwise be used to produce arable crops for human consumption. There is therefore a case that where grass is grown on potential arable land, it should be treated the same as other non-human-edible feed crops, and defined as high opportunity cost. This is not a niche consideration, as it is estimated that at global level 685 million hectares of land currently being used for grazing (around 35% of total grazed land) is actually suitable for growing crops.[29] In practice, however, converting permanent pasture to arable would be undesirable for a host of reasons, one being that conversion is likely to imply large releases of carbon dioxide. Grassland soils are the world's largest reservoir of terrestrial carbon (nearly 50% more than stored in forests worldwide), with conversion resulting in the loss of as much as 60% of soil carbon stocks.[30] It would also be undesirable to see a reduction in the use of temporary grass and herb leys on arable land where it is part of a fertility-building agroecological system. It is therefore important that a drive for low opportunity cost feed does not inadvertently disincentivise agroecological practices or encourage the conversion of permanent pasture to cropland. Indeed, current UK government policy supports farmers to convert arable land to grass, for environmental benefit.[31] It is also worth noting that in a LOC feed system we would not need more arable land, as by not using current arable land to feed animals, a huge amount more land than today would become available for human nutrition.

> SOME GRASSLAND NOT SUITABLE FOR CROPS MIGHT BE LOW OPPORTUNITY COST IN TERMS OF FOOD-FEED COMPETITION, BUT HIGH OPPORTUNITY COST IN TERMS OF BIODIVERSITY

SOME GRAZING LAND NEEDS TO BE USED FOR NATURE RESTORATION

The point around not promoting conversion of grassland to cropland is indicative of a wider critique of the food-feed competition concept in general, which is that it cannot be taken in isolation from the wider set of issues in which it sits. Just because grassland currently providing nutrition for animals could be converted to cropping, and therefore produce calories for humans more efficiently, this does not always outweigh other considerations such as the release of soil carbon from conversion. Nature restoration is another key imperative that must enter the discussion around land use - much grazing land, particularly marginal upland grazing that is not suitable for cropping, is well suited to nature restoration. If targets to restore nature are to be met then it is important that, alongside a host of other biodiversity-boosting measures, at least some current grazing land is used for these purposes. Some grassland not suitable for crops might therefore be low opportunity cost in terms of food-feed competition, but high opportunity cost in terms of biodiversity. The same may be true of other competing land uses such as renewable energy generation from biofuels, wind or solar. To add further complexity, well managed low density grazing may also be part of some solutions for managing land for biodiversity, so the issue of 'to graze or not to graze' is not always black and white.

FEED AND GREENHOUSE GAS EMISSIONS

Alongside nature restoration, a final issue to balance against food-feed competition in assessing livestock feed sustainability is greenhouse gas emissions. This is particularly key as the critical low opportunity cost feed for ruminants - grass - is also associated with higher methane emissions than other feeds such as cereals and concentrates.[32] It is worth noting that in general ruminants with a higher opportunity cost diet will have a proportionately higher CO_2 and nitrogen footprint versus methane, whilst those with a LOC diet will have a proportionately higher methane footprint. As a result some on-farm GHG mitigation strategies for ruminants recommend increasing concentrates and reducing high-roughage inputs that promote methane production, i.e. the opposite of what a LOC feed strategy would likely recommend. There are also options for reducing methane outputs from roughage, including new grass varieties and inoculants and additives for silage. A similar issue occurs at a macro-level with the observation that poultry and pigs have lower GHG emissions per kg of meat compared to ruminant animals, despite the fact that as grass eaters, ruminants have a far higher proportion of low opportunity cost feed in their diets. This has led to frequent recommendations in the past that sustainable diets should prioritise white meat over red meat. A low opportunity cost framework suggests that recommendations based solely on GHG impact per kg protein output need to be tempered by a wider view that takes in a range of metrics as well as questions around the differential impacts of methane and CO_2 in the atmosphere.

CONCLUSION: A TRANSFORMATIVE IDEA

This section has summarised some of the key ideas around low opportunity cost feed, which are based on the concept of food-feed competition. It has found that in practice the basic idea - of using arable land to produce crops for humans, and feeding livestock on grass and unavoidable by-products and waste - in reality entails a great deal of complexity. However, despite this, the core observation that feeding crops to humans is more efficient than feeding them to livestock remains true. For the purposes of this paper, we adopt a simplified view in order to paint a picture of a low opportunity cost feed system. We assume that all grass, food waste and by-products are low opportunity cost, and that all cereals and soy are low opportunity cost.

Despite the nuances and unanswered questions, shifting towards a system in which arable crops are prioritised for human nutrition - and livestock numbers are accordingly reduced - offers huge potential to reduce pressure on the world's land area. Such a system could look very different from today, and have huge implications for planetary health. But the vital caveat is that, in order to avoid perverse consequences, the promotion of low opportunity cost feeds needs to be done with sensitivity to a wide variety of other issues, and in the context of other goals such as greenhouse gas reduction, food security and nature restoration. Further research is required to map the contours of the real policy implications of these interactions.

The next section looks in detail at what goes into feeding the UK's livestock population today, and how much of it is low opportunity cost.

CHAPTER 3 > WHAT DO THE UK'S LIVESTOCK EAT?

The UK's population of livestock are fed on a combination of grass, compound feeds, individual 'straight' concentrate feeds, and direct agricultural inputs such as cereals, produced on-farm or purchased from other farmers. The following sections provide an introduction to the UK's livestock population and explore these feed categories in more detail.

Table 2 SUMMARY OF INPUTS TO UK LIVESTOCK NUTRITION

	NUTRITION FROM GRASS	COMPOUND FEED	STRAIGHT CONCENTRATES / OTHER	FEED FROM OWN OR NEARBY FARM
ESTIMATED SCALE[33]	90m tonnes estimated dry matter availability from 12.5m ha of grassland[34]	13.2m tonnes per year	7.5m tonnes per year	10m tonnes per year
DESCRIPTION	Grass can be grazed fresh, or fed dried (hay) or as silage. Nutritional characteristics vary depending on the land, its management and the season.	Manufactured blends of ingredients designed for the nutritional needs of individual livestock species and growth stages, often pelletised.	Individual ingredients including e.g. grains, by-products and soy fed by farmers as part of a diet. This includes inputs to Integrated Poultry Units.	Considerable volumes of animal nutrition are produced on farms or purchased direct from other farmers e.g. grains, crop silage.
LIVESTOCK SPECIES	Ruminants	Ruminants and non-ruminants	Ruminants and non-ruminants	Ruminants and pigs
UK SELF- SUFFICIENCY	Yes	<50%	<50%	Yes

3.1 THE UK IS HOME TO OVER 230M LIVESTOCK ANIMALS

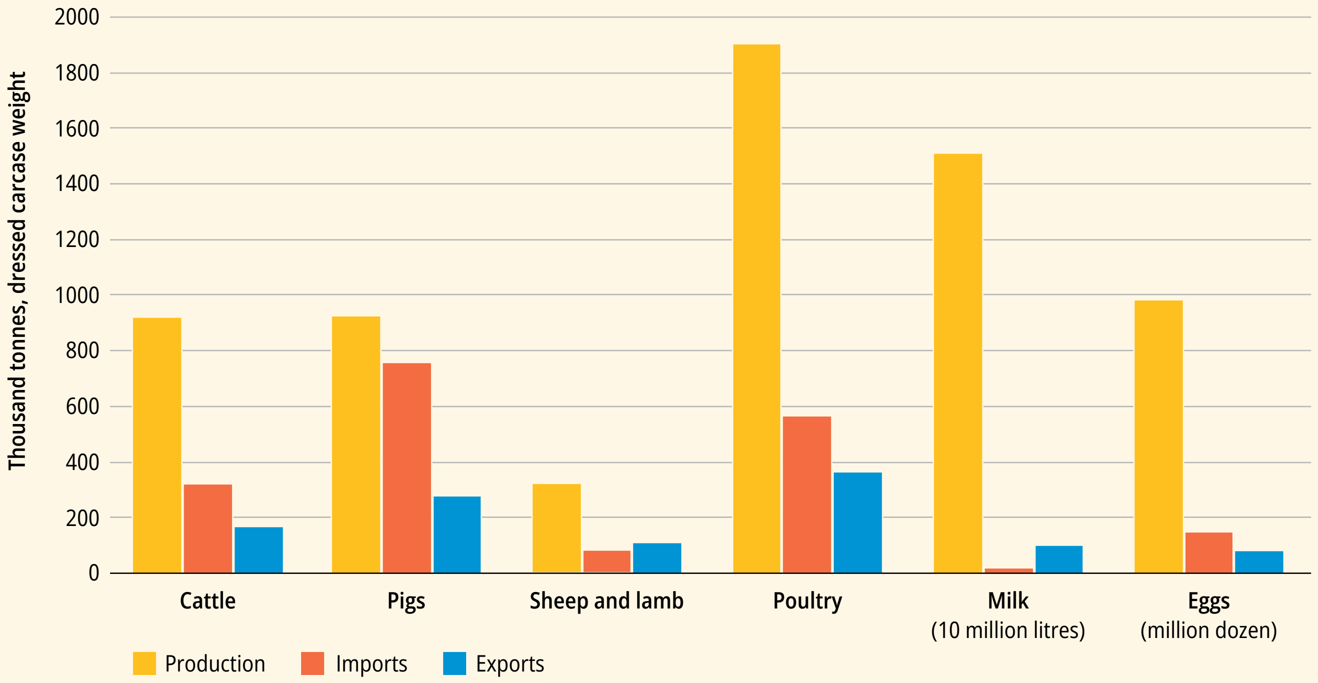
> UK HOUSEHOLD POULTRY MEAT PURCHASES HAVE DOUBLED SINCE THE 1970S

At the time of Defra's June survey in 2019, the UK's livestock population included 9.7m cattle, 33.6m sheep, 5m pigs, and 187m poultry birds.[35] Over the year as a whole this equated to the production of 919,000 tonnes of pork, 917,000 tonnes of beef and veal, 318,000 tonnes of lamb and mutton and 15 billion litres of milk.[36] For poultry the total production for 2019 was 1.9m tonnes of meat from the slaughter of over 1.1 billion birds, and almost 12 billion eggs.[37] Despite these huge numbers, the populations of most livestock species in the UK have been on a downward trajectory over the past few decades, with cattle declining from 12m in 1996 (-20%), sheep and lamb from 42m (-20%), and pigs from 7.6m (-33%).[38] This is in line with long-term per capita declines in household purchases of beef, lamb and pork (which are around half of what they were in 1974);[39] the declining profitability of farming; and a rise in imports over the last 20 years.[40] Poultry have not followed the downward trend, with household poultry meat purchases doubling since the 1970s, and numbers of birds continuing to rise since 2010.[41] Almost all poultry is now produced in highly industrialised intensive poultry units.

Despite a rise in imports, the majority of the UK's demand for animal source foods is still met through domestic production (see Figure 4 below). Relative to consumption, around 50% of the UK's pork is imported, whilst the figure is 30% for beef and around a quarter for lamb and poultry. Major meat supplying countries to the UK are Denmark, Germany and the Netherlands for pork; Ireland for beef; and the Netherlands and Thailand for poultry and poultry products.[42] A proportion of UK production is also exported, including up to a third of sheep and pig meat, and just under 20% of cattle and poultry.[43] The impact of Brexit and ongoing trade negotiations are likely to change this picture. On balance, as a measure of theoretical self-sufficiency, net imports account for around 35% of pork consumption, 15% for beef, and less than 10% for poultry and eggs. The UK is a net exporter of lamb and milk.

Figure 4

DOMESTIC SUPPLY, IMPORTS AND EXPORTS OF ANIMAL PRODUCE, 2019



*Milk is measured in ten million litres. **Eggs are measured in million dozen.
Source: Agriculture in the United Kingdom 2019, Defra[44].

3.2 GRASS PROVIDES OVER 75% OF THE DIET FOR RUMINANTS

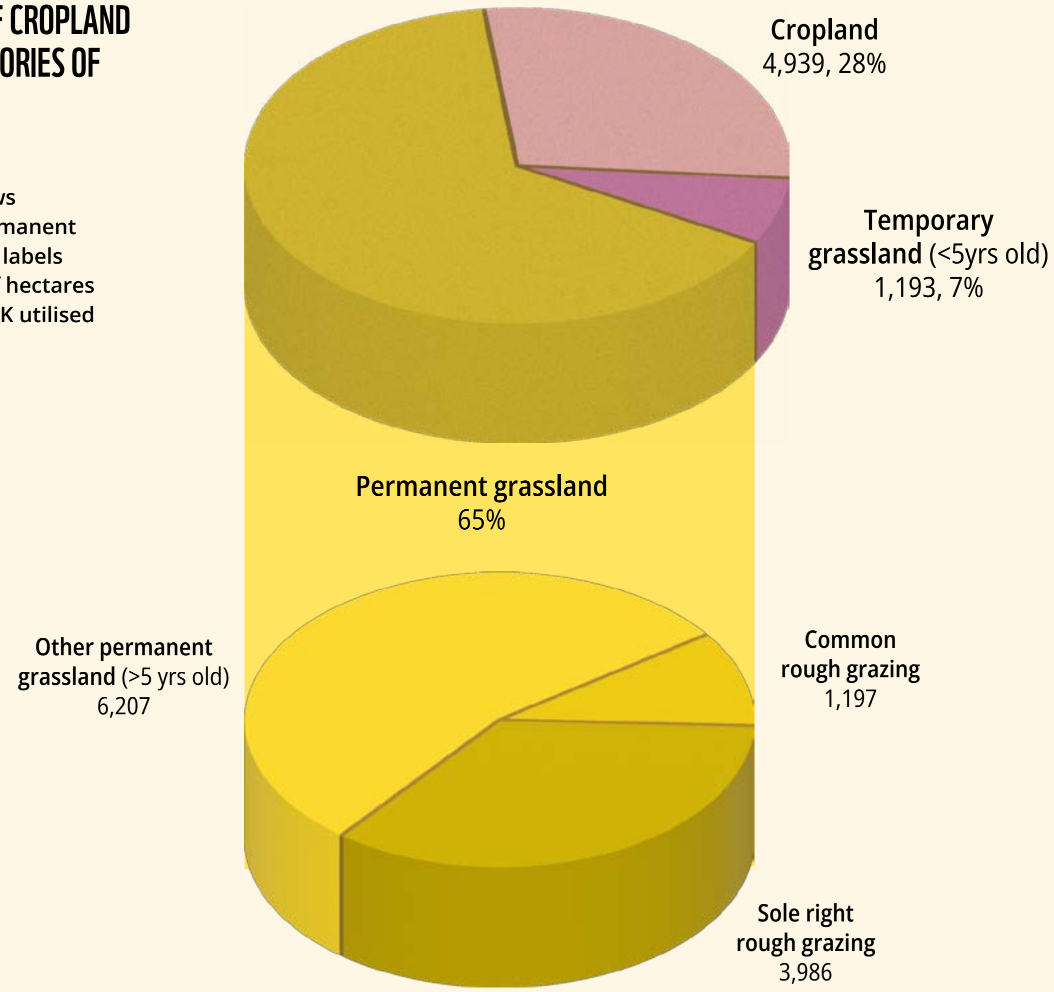
THE MAJORITY OF THE UK'S AGRICULTURAL LAND AREA IS GRASS

The UK has a total of 12.5m ha of grassland, which supports 75%-85% of the dry matter dietary intake of adult ruminants.[45] This is a much higher proportion than countries with lower amounts of grass or where livestock production systems focus on intensive operations such as concentrated animal feedlots (CAFOs). In total, grass represents 67% of the UK's total agricultural area, and 72% of the UK's utilised agricultural area (UAA) compared to just 28% used as cropland (see Figure 5).[46] The vast majority of agricultural grasslands in the UK are used for animal production, either for grazing or to produce hay and silage for fodder. Some small areas of grassland are no longer used for production but are maintained in good agricultural condition (1% of permanent grasslands in the UK in 2016)[47] or have other uses such as growing grass used for renewable energy generation.[48]

Figure 5

UK UTILISED AGRICULTURAL LAND USE SHOWING AREA OF CROPLAND AND DIFFERENT CATEGORIES OF GRASSLAND

Secondary pie chart shows subcategories within permanent grassland. Values in data labels give area in thousands of hectares and percentages are of UK utilised agricultural area.



Source: Defra, 2020

THE UK USES A MIX OF GRAZING AND INDOOR HOUSING FOR RUMINANTS

Many ruminants spend large parts of the year outside eating mainly grass, especially sheep and cattle reared for meat. Animals spend a greater proportion of time indoors during the winter months when the nutritional quality of grazing may be insufficient and it can be harder to maintain animal health outdoors. Animals are also more often indoors when lambing or calving, to allow for closer attention. When animals are housed indoors temporarily or permanently, or when grass production for grazing is insufficient, ruminants are also fed grass that has been cut, dried and stored as hay and silage (grass and other green fodder crops stored without being dried), in addition to concentrate and compound feeds (detailed in the following section). Hay and silage may represent 10-20% of the dietary composition of adult female ruminants, especially dairy cows.[49]

> ONLY 30% OF UK DAIRY FARMS MAINTAIN THE TRADITIONAL SYSTEM OF 100% OUTDOOR GRAZING DURING THE SUMMER

Most of the UK's farms with cattle (87%) use a mix of grazing and indoor systems, with 9% grazing year round and 4% of farms housing their cattle permanently indoors.[50] Dairy cows are more likely to spend a greater portion of time indoors, with estimates of between 5%[51] and 20%[52] of dairy farms permanently housing their cattle indoors, equating to around 40,000 head of livestock.[53] The proportion of grass-based feed is lower in these cases. There is now a trend towards increasing dairy farm size and increased indoor rearing, allowing closer control over health and nutrition, and increased milk yields. While dairy mega-farms housing thousands of animals indoors all year round are still relatively rare,[54] only 30% of dairy farms maintain the traditional system of 100% outdoor grazing during the summer.[55]

UK GRASSLAND VARIES IN PRODUCTIVITY, WITH SIGNIFICANT AREAS OF MARGINAL LAND

Around 90% of UK grasslands are classed as permanent grassland - areas of land which have been used to grow grasses and other herbaceous crops for at least 5 consecutive years. In addition to this, temporary grasslands - which are less than 5 years old and commonly grown as part of a crop rotation - covered around 7% of the UK UAA in 2019 (1.2m hectares).[56] Whilst these temporary grasslands might within some frameworks technically be classed as high opportunity cost since they are grown on arable land, they are also often part of more sustainable rotational farming systems that use legumes and green manures to enrich the soil with lower inputs of artificial fertilisers. Disincentivising the production of grass and legume-based feed from these temporary grasslands would therefore be counterproductive in the bigger picture. For this reason temporary grasslands have been classed as low opportunity cost in this paper.

Most grassland (95%) is classed as 'improved' or 'semi-improved,[57] meaning that it has received fertilisers, or undergone soil mobilisation and sowing of selected varieties, which can be used for more intensive grazing and production of hay and silage. A mixture of species may be grown in addition to grasses, including legumes, which improve soil fertility and increase the protein content of forage. Lowland pasture generally receives greater levels of 'improvement', and these support lower levels of biodiversity. The potential dry matter productivity of improved lowland pasture is estimated at 20 tonnes per hectare, compared to a UK average productivity of 7.3 tonnes.[58]

Rough grazing land makes up 46% of the UK's permanent grassland. This refers to areas which usually have poor soils and lower productivity and support only extensive - low density - grazing, particularly of sheep. These include areas of mountains, hill, heathland and moorland. Much of this is officially categorised under Less Favoured Area (LFA) status - land that is considered of marginal economic value when the value of output is compared to the cost of the inputs.

These areas are substantial, with 80-90% of land in Wales and Scotland classed as LFA. And in England, almost a third of beef cattle (27%) and 40% of female breeding sheep are produced on LFA grazing livestock farms.

A small proportion of grasslands are classed as semi-natural.[59] These often support high biodiversity, particularly of plants and invertebrates.[60] The productivity of semi-natural grasslands for livestock is low; average annual hay yields are less than 30% of the volumes harvested from improved grasslands and the digestibility and nutrient content of the forage is also much lower. Semi-natural grasslands now comprise only around 2% of UK grasslands - mostly within protected areas - having declined by 90% since 1945, primarily through conversion to 'improved' grasslands or to arable land. This was driven by post-war food security policies and subsidy regimes. Some semi-natural grasslands are managed using periodic and low-density grazing, usually for the purposes of biodiversity conservation rather than livestock productivity; suitable stocking rates are half to a third of those for improved grasslands and often hardy, traditional breeds are used instead of breeds chosen for high productivity in terms of meat or milk production.[61]

FUTURE AVAILABILITY OF GRAZING LAND NEEDS TO BE CONSTRAINED BY BIODIVERSITY AND CLIMATE IMPERATIVES

> LIVESTOCK GRAZING COMBINED WITH TREES CAN DELIVER ECOSYSTEM BENEFITS INCLUDING CARBON SEQUESTRATION AND ENHANCED BIODIVERSITY

Not all of the UK's existing grassland should be considered available as a nutritional input to a low opportunity cost feed system. Substantial changes in the use of grassland will be required to meet national aims in nature restoration. The UK's National Food Strategy (NFS) suggests that the least productive 20% of land (much of which is grazing, and which produces only around 3% of the food in the UK) should be released from intensive agricultural production. The Committee for Climate Change similarly estimates that 21% of agricultural land needs to be prioritised for carbon sequestration in order to meet climate change targets.[62] Some of this would imply removing land entirely from production to be used instead for woodland or the restoration of habitats such as peat bogs - the NFS suggest around 5-8%.[63] However the remainder of the land prioritised for environmental outcomes could still support some low intensity grazing in the context of a more 'agroecological' food production system for the UK[64]. Existing small pockets of production in the UK provide some guide as to what this 'less and better' grazing might look like, for example semi-natural grasslands, which use low-intensity extensive grazing management, often involving hardy heritage livestock breeds suited to such habitats. Wood pasture – in which livestock grazing is combined with an increased number of trees in a landscape – is also less intensive in terms of animal numbers, but delivers significant ecosystem services including carbon sequestration and enhanced structural and species diversity.

Upland areas – the majority of which are classified as Least Favoured Areas or Severely Disadvantaged Areas – require particular consideration. In England, 28% of beef cows and 41% of female breeding sheep are from LFA grazing livestock farms.[65] These areas generally have thin soils and steep land. If they are to be used for agricultural production at all, they are best suited for livestock farming, however, livestock production in these areas sometimes offers poor returns and profitability is reliant on agricultural subsidies.[66] These areas may offer some of the best options for removing land from grazing or reducing grazing to very minimal levels.

Farmers will require support for such transitions in production. Incentives to farmers would need to make the delivery of environmental objectives more attractive than conventional farming in order to drive land management for carbon sequestration and nature conservation. Changing land use can involve a delay before the new use becomes profitable and there are often costs of establishing new practices and systems. There will therefore need to be systems to provide financial support to cover these up-front costs as well as to provide the appropriate skills, training and information that farmers will need when adopting new systems.[67]

3.3 UK LIVESTOCK CONSUME 31M TONNES OF NON-GRASS FEED INPUTS EVERY YEAR

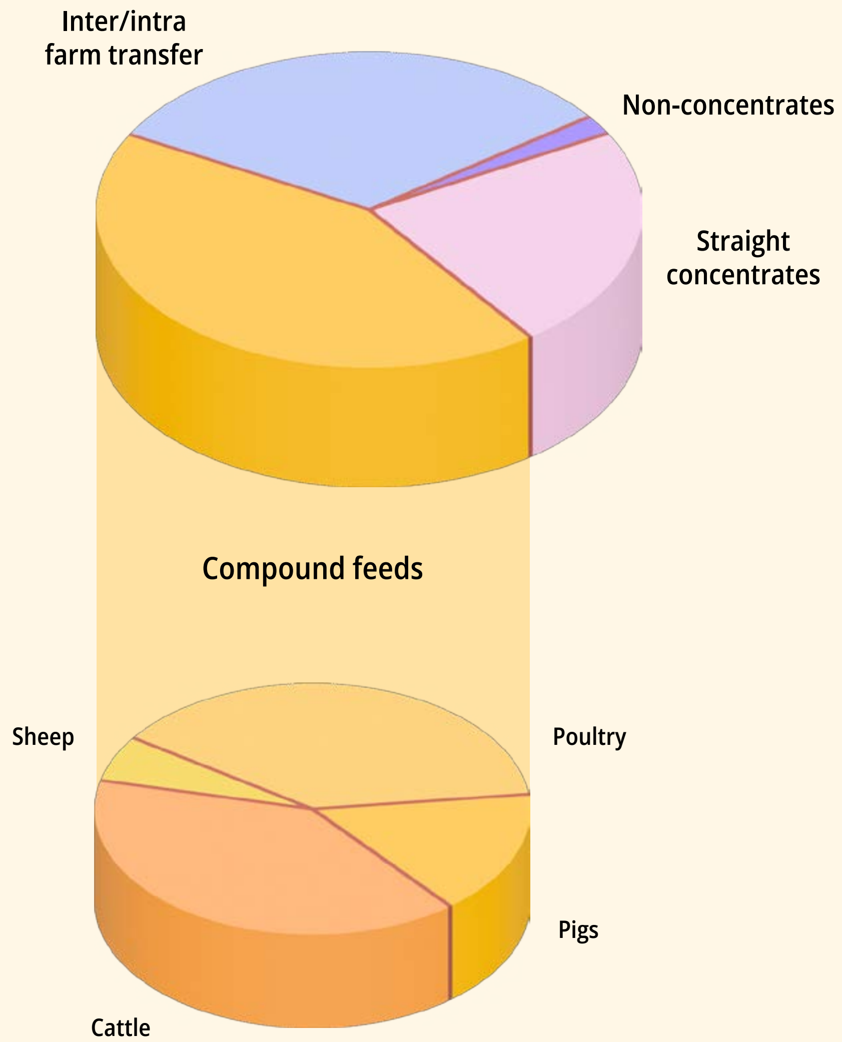
> UK FARMERS SPEND APPROXIMATELY £5.5BN EVERY YEAR ON FEED FOR THEIR LIVESTOCK

In addition to grass for ruminants, the UK's livestock receive nutrition in a variety of other forms. According to Defra data, farmers in the UK spend approximately £5.5bn every year on feed for their livestock.[68] Around a third of this feed by weight consists of crops grown on-farm or purchased directly from other local farms - this could be in the form of grains, other crops, or maize or wheat wholecrop silage, including leaves and stems.[69] Just under a quarter of feed by weight consists of individual concentrate ingredients known as straights, mainly purchased from feed merchants. The largest category is compound feeds, in which ingredients and additives are blended by manufacturers to contain balanced nutrition products for livestock at different stages of growth. Compounds make up 44% of all non-grass feed by weight, and 61% by value, due to the additional cost of ingredients, manufacturing, value-add and logistics. Additional government data is available to show the destinations of manufactured compound feed, indicating that around 80% is used for poultry (majority broilers) and cattle (primarily dairy), in roughly equal portions. Pigs consume 15% and sheep only 7% (see Figure 6). Concentrate and compound feed for aquaculture is not included in these figures.

Figure 6

NON-GRASS FEED IN THE UK, 2019, BY TONNAGE.

Compound feed (excluding production from integrated poultry units) is further split by use for individual livestock species.



Source: Agriculture in the UK 2019 Defra

SPLITTING OUT THE INPUTS TO NON-GRASS FEED

> CROPS, MOSTLY CEREALS AND MOSTLY PRODUCED IN THE UK, MAKE UP 63% OF LIVESTOCK FEED

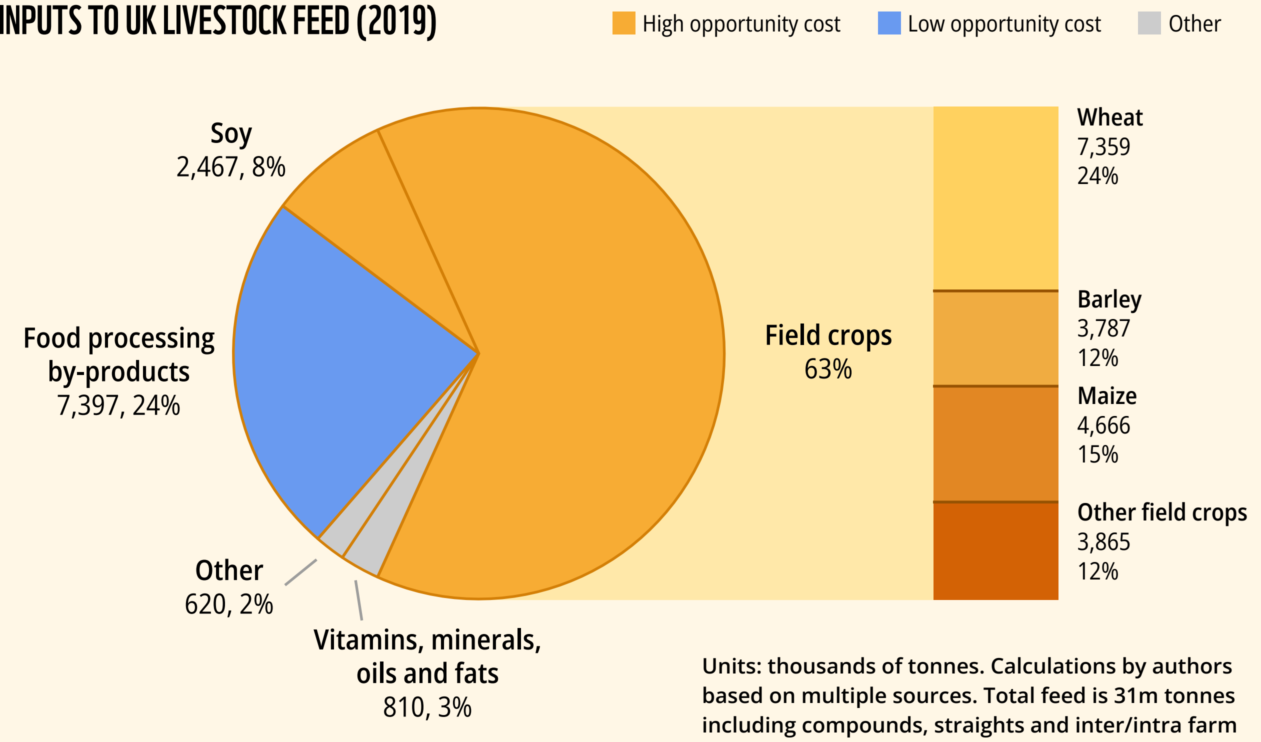
In order to determine how livestock feed from non-grass sources stacks up in terms of opportunity cost, it is necessary to split out the ingredients that make up the total of the 31m tonnes compound, concentrate and on-farm feed. Good data are available for the component ingredients of the compound feed produced annually by manufacturers. However, getting a detailed quantitative view of the inputs to the remaining feed categories recorded by Defra is more challenging. For this project we have drawn on a variety of additional data sources - including specific Northern Ireland feed production data, direct correspondence with Defra, UK crop production data, and trade data - in order to produce an estimated breakdown of what goes into UK feed. Further details on methodology are provided in Appendix 1.

Our estimates suggest that inputs to non-grass feed come from a wide variety of sources. The main component is agricultural crops, mostly cereals, which make up 63% and are present in compound feed, straights and farm-based feed. Soy-derived feeds account for 8%. 17% consists of by-products from food processing and manufacturing, alongside a small quantity of surplus food diverted from manufacturing and retail. Total by-products rise to 24% when oilseed cake and meal are included. Other inputs include unclassified feed ingredients used in compound feeds, and smaller volume additives and ingredients such as vitamins, minerals, oils and fats. These inputs are detailed in the following charts (Figure 7 and Figure 8) and explored in more detail below. The charts use orange to indicate high food-feed competition opportunity cost, blue to indicate low opportunity cost and grey to indicate N/a or unknown opportunity cost.

Where possible, it has been indicated in the text whether inputs are domestically produced or imported, however, complete figures are not available. For compound feed alone, better data is available, with government sources indicating that in 2017 6.1m tonnes (44%) of the 13.9m tonnes of compound feed manufactured that year were imported, the majority from outside the EU.[70]

Figure 7

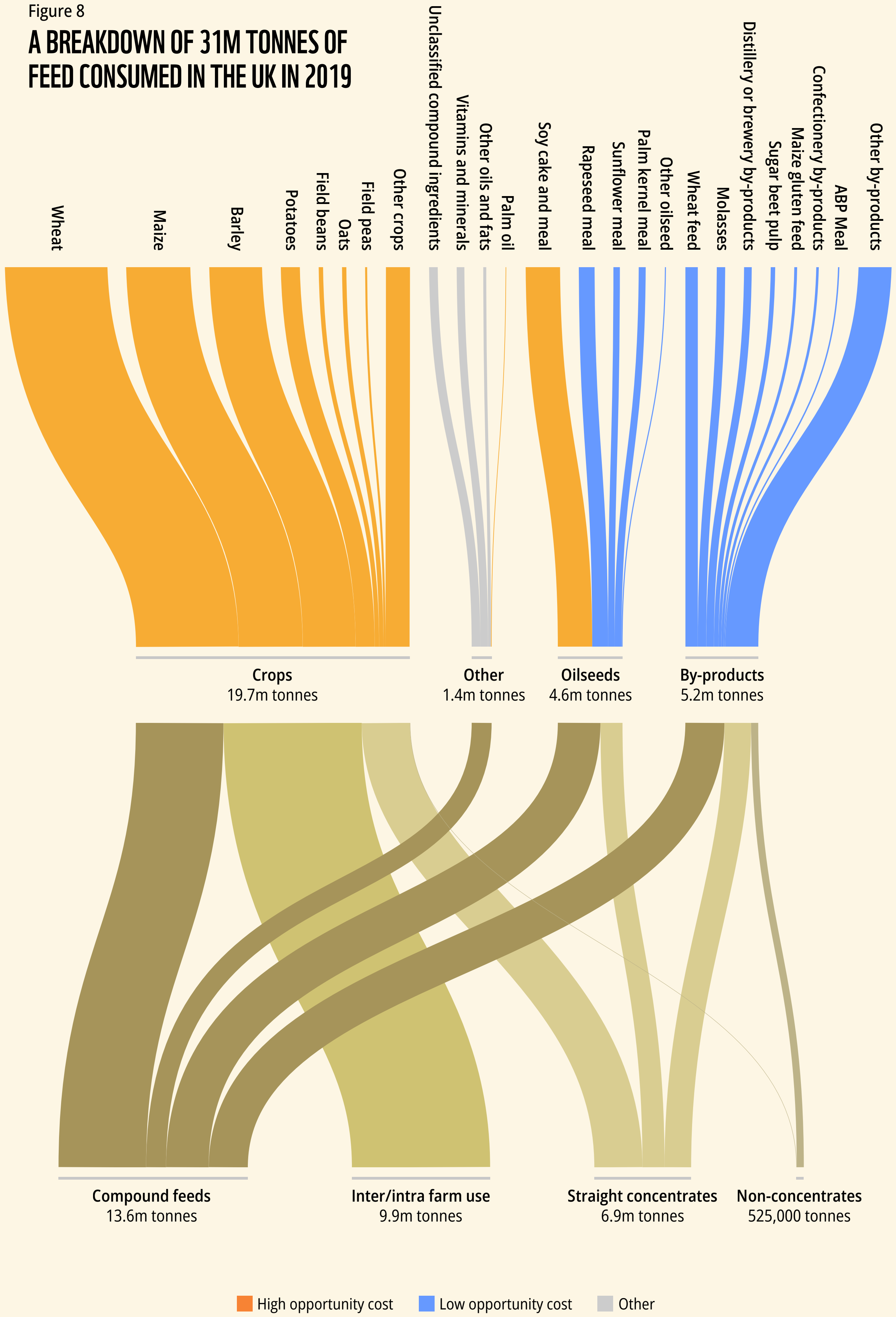
INPUTS TO UK LIVESTOCK FEED (2019)



Units: thousands of tonnes. Calculations by authors based on multiple sources. Total feed is 31m tonnes including compounds, straights and inter/intra farm transfer. See methods in Appendix 1 for details.

Figure 8

A BREAKDOWN OF 31M TONNES OF FEED CONSUMED IN THE UK IN 2019



NON-GRASS FEED > CROPS

> FEED PRODUCTION REPRESENTS 41% OF UK CROPLAND, AND REMOVING THESE INPUTS FROM LIVESTOCK FEED COULD FREE UP 1.9M HECTARES OF LAND IN THE UK FOR OTHER USES.

Crops, mostly cereals, and mostly produced in the UK, make up 63% of livestock feed. This includes not just the grains but also sometimes the stems and leaves of plants when used as forage or wholecrop silage.[71] Around 50% of the crops used as feed are grown on-farm or bought direct from other farms. Some of the remainder, especially grains used in manufacturing compound and concentrate feedstuffs, are purchased on commodity markets, where price fluctuations will affect decisions about what to buy, and when. Non-cereal crops make up only a small proportion of the total. These include surplus potatoes, as well as field beans and peas that are grown for animal feed. No specific numbers exist for forage crops such as kale and beet, but these are assumed to constitute some of the balance of crops not accounted for by cereal crops, potatoes, beans and peas.

While specific figures are not available for the proportion of the cereals used in animal feed that are imported, it is clear that the majority of cereals consumed in the UK, regardless of whether they are fed to animals or going directly to feed people, are grown domestically. Wheat imports equate to only 7.5% of the tonnage produced domestically in 2019.[72] Whilst 1.2m tonnes of wheat were imported, a similar tonnage was exported, meaning the UK had around 99% theoretical self-sufficiency. Imports of barley in 2019 were only 0.8% of production, and for oats 2.1%. The percentage of imported maize is higher, but precise figures are not available. In general, while imported maize is grain-based, domestic maize tends to be fed as silage.

For the purposes of this study, all of the feed inputs in this category have been treated as high opportunity cost, as, whether they are edible by people or not, they are likely grown on arable land that could have been used to grow food directly for human consumption. 51% of wheat, the UK's biggest crop, and 64% of barley, the second biggest, were used for animal feed in 2019. Maize production in the UK has grown to 228,000 ha in 2019 from only 8,000 ha in 1973, with 60-70% used for animal feed and most of the remainder for energy generation from anaerobic digestion.[73] Collectively feed production represents 41% of UK cropland, and removing these inputs from livestock feed could free up 1.9m hectares of land in the UK for other uses (Table 3).

Table 3

AREA OF KEY UK CROPS USED FOR ANIMAL FEED, 2019

	Wheat	Barley	Maize	Oats	Field Peas	Total
Area of land under crop (1000 ha)	1,816	1,162	228	182	41	3,429
Fraction used for animal feed	51%	64%	~60%*	36%	92%	
Area of land used for animal feed (1000 ha)	926	774	137	66	38	1,911
Animal feed area as a proportion of all utilised cropland	20%	16%	3%	1%	0.8%	41%

*estimated as no data available

PROPORTION OF CROP CONSUMED BY ANIMALS

= 10,000 ha

Source: Agriculture in the UK 2019.

As discussed in Section 2 above, there are some caveats around stopping the flow of crops to livestock, including that some level of over-production of cereals is necessary for food security, and that livestock use lower quality crops that cannot be sold into food supply chains, allowing farmers to hedge risk and regain some value from sub-optimal crop performance due to weather conditions or other factors. It is also worth noting that crops suitable for animal feed can often grow on poorer soils that might be less well suited to crops for human consumption. For example, triticale - a hybrid of wheat and rye mainly used for animal feed - can grow on poorer soils than wheat. It may therefore not always be possible to grow successful yields of human-edible crops on the land currently used to grow animal feed crops. However, no data is available on this, so it has not been taken into account in the above statistic.

The following table provides a summary of the crop-based inputs to feed.

Table 4 **CROP-BASED INPUTS TO UK LIVESTOCK FEED**

	DESCRIPTION	INDICATIVE NUTRITIONAL BREAKDOWN	PRIMARY LIVESTOCK SPECIES	ESTIMATED % OF FEED (NON-GRASS)
CEREALS				52%
WHEAT	Around 50% of wheat in the UK is used in animal feed.[74] This is either wheat that is grown specifically for feed, is surplus to requirements, or does not meet quality specifications. It can be fed as a grain, processed or as wholecrop silage.	Protein: 13% Fibre: 3% Starch: 70%	All	24%
BARLEY	65% of barley in the UK is used as animal feed. Globally the figure is around 85%. Barley forage (stems / straw) can also be fed to livestock.	Protein: 12% Fibre: 5% Starch: 60%	Cattle and pigs	12%
MAIZE (CORN)	Maize may be fed whole or flaked, which is more digestible. UK maize is fed as silage. Compared to other cereals, a higher proportion of maize grain is imported.	Protein: 9% Fibre: 2.5% Starch: 73%	All	15%
OATS	34% of oats in the UK are used as animal feed. Globally 70% of oats are used as feed. Oats are now less widely used in feed than during the 20th century.	Protein: 11% Fibre: 14% Starch: 40%	Ruminants	1%
OTHER				12%
FIELD BEANS (FAVA / BROAD BEAN)	Field beans are used as both feed and fodder (hay, silage and straw). The beans can be used as an alternative to soy. Commonly used in crop rotations as a nitrogen fixer.	Protein: 29% Fibre: 9% Starch: 45%	Cattle and poultry	<1%
FIELD PEAS	Peas can be fed raw or processed, and remnant straw used as forage. Nutritional value is variable. Can be used as a soy alternative. Commonly used in crop rotations as a nitrogen fixer.	Protein: 24% Fibre: 6% Starch: 51%	Cattle, pigs, poultry	<1%
POTATOES	Surplus potatoes, or those that don't meet quality standards, are often used for animal feed - representing around a quarter of the total potato harvest. Fed raw, cooked or ensiled.	Protein: 11% Fibre: 2.5% Starch: 72%	All	5%
OTHER	Other crops are mostly fed on farm, such as forage beets, kale, turnips - these are either grazed in the field or harvested and fed to animals.	Variable	Ruminants and pigs	5%

NON-GRASS FEED > FOOD PROCESSING BY-PRODUCTS

By-products from food processing, including by-products from the production of sunflower, rapeseed and palm oil represent around one quarter of all livestock feed inputs. These come from a wide variety of sources, listed opposite in Table 5, and are highly variable in nutritional characteristics, availability and quality. Compared to cereals, a greater proportion of by-products are imported from overseas, with some of the main import categories being sugar cane manufacturing by-products such as molasses (widely used as a binder and mixer for other feeds), sunflower meal, palm kernel expeller and brewing and distilling by-products.[75] Others are primarily by-products of UK-based food processing, such as the refining of sugar beets, and wheat milling.

As per the discussion in Section 2, some of these 'by-products' are technically edible, such as wheat bran, molasses and whey, but a large enough market does not exist to utilise the full volume of production. For the purposes of this paper, all have been identified as low opportunity cost. Other categories worthy of discussion in this regard include confectionary by-products, which are listed in Defra data on compound feed ingredients but without any additional information. It is unknown whether these are genuinely by-products, or rather surplus products such as sweets graded out of the supply chain for quality reasons, or baked goods that remain unsold, both of which are routinely found in animal feed. They have nonetheless been included here as by-products. The category of milk products and by-products is also likely to include some human edible cow's milk that is surplus.

The animal by-products category deserves particular attention. This refers to the processed by-products of the meat processing industry that do not enter the human food chain, for example bones, heads and feet. Currently, only very limited categories of animal by-products can be used, for example animal fats, hydrolysed protein, and gelatine and collagen from non-ruminant animals. Farmed fish can be fed processed animal protein (PAP) from pigs and poultry. These strict controls were put in place in the 1990s during the BSE crisis. These rules are now to be amended in the EU to allow PAP from pigs and insects to be fed to poultry, chicken PAP to be fed to pigs, and gelatine and collagen from ruminants to be fed to non-ruminants, paving the way for potential increases in low opportunity cost feedstuffs.[76] For now the original rules will still apply in the UK.

The following table provides a summary of by-product inputs to animal feed:

Table 5 BY-PRODUCT INPUTS TO UK LIVESTOCK FEED

	DESCRIPTION	INDICATIVE NUTRITIONAL BREAKDOWN	PRIMARY LIVESTOCK SPECIES	ESTIMATED % OF FEED (NON-GRASS)
PRIMARY PROCESSING OF CEREALS				5%
WHEAT FEED	Wheat feed is a by-product of flour milling. It comprises wheat bran, endosperm and other starch screenings. For every tonne of wheat milled only 20kg of wheat feed is produced.	Protein: 17% Fibre: 10% Starch: 23%	Cattle, pigs, poultry	3%
RICE BRAN EXTRACTIONS	Rice bran is a by-product of rice processing - the bran is further processed for animal feed and may include the oil or be de-fatted.	Variable	Pigs	<1%
MAIZE GLUTEN FEED	Maize gluten feed is a by-product of the wet milling of maize for starch or ethanol production, consisting of bran and maize steep liquor.	Protein: 22% Fibre: 8% Starch: 22%	Cattle	1%
PROCESSING OF OTHER CROPS				4%
MOLASSES	A by-product of the refinement of sugar, used as an energy source and binder in compound feeds.	Protein: 5.5% Fibre: 0.1% Sugars: 64%	Ruminants	2%
SUGAR BEET PULP	The fibrous remnant of processing of sugar beets once sugar has been extracted.	Protein: 9% Fibre: 21% Starch: 0.5%	Dairy cattle	1%
CITRUS AND OTHER FRUIT PULP	Residues after extracting juice from citrus fruits can be fed fresh or dried into pellets for export.	Protein: 7% Fibre: 14% Starch: 0.05%	Ruminants	<1%
BY-PRODUCTS OF OILSEED PROCESSING				<8%
RAPESEED (CANOLA) MEAL	Rapeseed is grown primarily for oil (for food, biofuel and industrial uses). Meal is the solid by-product of oil extraction. It is often substituted for soy meal.	Protein: 38% Fibre: 14% Starch: 7%	All	4%
PALM KERNEL EXPELLER	The solid residue of the extraction of oil from the palm kernel. Helps produce hard carcass fat and can boost butterfat levels.	Protein: 17% Fibre: 20%	All, mostly ruminants	2%
SUNFLOWER MEAL	A by-product of extraction of oil from sunflower seeds.	Protein: 32% Fibre: 28%	Cattle	1%
OTHER OILSEED MEAL	'Other oilseeds' includes linseed, coconut or copra.	Variable	Cattle	<1%
MANUFACTURING BY-PRODUCTS				3%
CONFECTIONARY BY-PRODUCTS	Likely to be surplus baked goods and sweets. These can be fed directly to animals or processed into meal.	Variable, typically low fibre, high starch	Ruminants, pigs, poultry	1%
DISTILLING AND BREWING BY-PRODUCTS	By-products from the production of whisky, beer or ethanol include wet grain residues (barley, wheat or maize), concentrated liquid residues and yeast.	Variable, but can be high protein up to 30%. Yeast has 36-50% protein.	Ruminants	2%
ANIMAL BY-PRODUCTS				<2%
ANIMAL BY-PRODUCTS	Rendering of meat industry by-products like bones, necks, heads, feet etc, processed animal protein (PAP), gelatine and meal.	Variable depending on product but can be high protein and fat	Specific rules apply	1%
MILK PRODUCTS AND BY-PRODUCTS	Whey powder derived from cheese production is fed to infant ruminants as a milk replacer. Skimmed milk powder is sometimes also used.	Starch: N/a Protein: 12.5% Fibre: N/a	Cattle	<1%

> SOYMEAL IN FEED IS HIGH OPPORTUNITY COST BECAUSE SOY DRIVES DEFORESTATION AND CONVERSION IN SOUTH AMERICA AND THE US

SOY CAKE AND MEAL

Like rapeseed and other meals, soy meal is the solid residue left after crushing the raw ingredient (in this case soybeans) to produce oil. However, unlike the oilseeds listed above, soy meal is the primary generator of value from soybeans, and therefore needs to be considered as the prime driver of soybean production. All soy in animal feed is therefore classed as high opportunity cost for this paper. In addition there is a key cause for concern around soy's role as a driver of deforestation in South America. Soy cake and meal is the largest single category of non-cereal livestock feed ingredients imported into the UK, at just under 2 million tonnes per year.[77] In addition, around 750,000 tonnes of whole soybeans are imported every year, the vast majority for animal feed. Some are fed whole, but most are crushed and the resulting meal used in animal feed.[78]

The use of soy cake and meal has grown massively since the 1960s, almost entirely driven by animal feed (see Figure 9). Whilst soy meal is edible and is used for the production of soy flour for commercial baking and other applications, 98% is used for animal feed. Soy has become so important in animal feed for a number of reasons. In particular, it is highly palatable, with protein content as high as 50%, and a balanced amino acid profile. Soy use also increased in the 1990s when bone meal was banned for use in feed in the EU due to the outbreak of BSE. The majority of soy meal globally is used in pig (29%) and poultry (53%) farming, with relatively smaller amounts in aquaculture and dairy production. Comparatively little is used overall in the production of ruminant meat. Small volumes of soybean oil may also be found in livestock feeds as a fat and energy supplement.

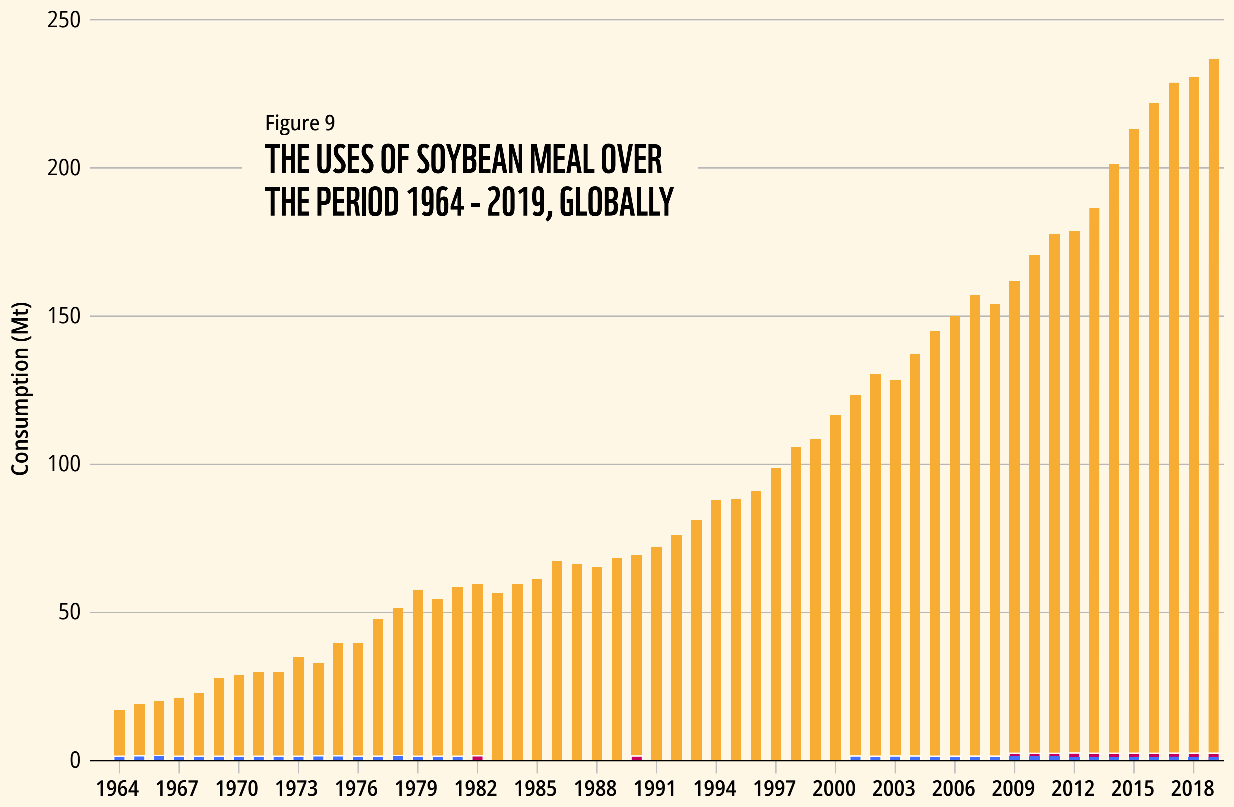


Figure 9
THE USES OF SOYBEAN MEAL OVER THE PERIOD 1964 - 2019, GLOBALLY

Figure by FCRN, data from the USDA PSD.[79]

Table 6 **SOY CAKE AND MEAL IN UK LIVESTOCK FEED**

	DESCRIPTION	INDICATIVE NUTRITIONAL BREAKDOWN	PRIMARY LIVESTOCK SPECIES	ESTIMATED % OF FEED (NON-GRASS)
SOY CAKE AND MEAL	Currently the most important protein source for livestock feed, it is the co-product of soy oil from crushing soybeans.	Protein: 48% Fibre: 4% Starch: 7%	Poultry, pigs, dairy	8%

OTHER INPUTS

Finally, there are a range of other inputs to livestock feed that while nutritionally significant, are less significant in terms of overall tonnage. Vitamins and minerals are used to supplement feed to enhance animal nutrition. Most significant in this category in volume is likely to be calcium carbonate (often limestone), used to aid bone and eggshell development, and often used as an inert carrier for other additives.

Oils and fats are included in animal rations as a source of energy as well as fatty acids and fat soluble vitamins. There are a number of sources for these including soybean oil, cottonseed, rapeseed and animal fats. Worth noting particularly for their links to deforestation are palm-derived oils and fats - not only palm oil (40-50,000 tonnes used annually), but also palm fatty acid distillate (16-20,000 tonnes).[80] Palm oil itself should be classified as high opportunity cost since it is the main product of oil palm production, produced from crushing the fruit of the oil palm. Palm fatty acid distillate (PFAD), a residue from refining crude palm oil, should be classed as a by-product, as it is produced at around 3.7% of the volume of the main palm oil yield and is not a significant driver of overall value. The remaining vitamins, minerals, oils and fats have been classified as n/a since they are from a range of sources, including synthetic manufacturing, that have not been fully evaluated in the scope of this project, and represent only a small percentage of the total feed.

Table 7 **OTHER INPUTS TO UK LIVESTOCK FEED**

	DESCRIPTION	INDICATIVE NUTRITIONAL BREAKDOWN	PRIMARY LIVESTOCK SPECIES	ESTIMATED % OF FEED (NON-GRASS)
Fe Ca MINERALS AND VITAMINS	Includes macro (calcium, phosphorus etc) and micro (iron, copper, zinc etc) components.	N/a	All	2%
OILS AND FATS	Oils and fats can be used to supplement diets. These are either animal-based products of rendering or vegetable oils like corn, soybean, sunflower and palm.	N/a	Cattle, poultry	1%

3.4 FOOD SURPLUS AND WASTE - THE MISSING LOC FEED?

The above data indicate that around a quarter of the UK's non-grass animal feed inputs are low opportunity cost, consisting primarily of by-products from food processing and manufacturing, sourced from both the UK and abroad. Conspicuous by their absence in these statistics are any data around the quantities of food surplus and waste that end up in animal feed.

> **IT IS ESTIMATED THAT 660,000 TONNES OF FOOD SURPLUS AND WASTE IS USED TO FEED LIVESTOCK**

The current official statistics around compound feed manufacture make no mention of food waste and surplus. As noted above it is possible that the 182,000 tonnes of confectionary 'by-products' recorded annually are misclassified and actually represent former foodstuffs. Other estimates, however, suggest that the volume of food surplus / former foodstuffs entering the animal food supply chain should be at least three times higher than this. WRAP estimates the figure to be 660,000 tonnes in 2015,[81] which would represent around 2% of all concentrate feed.[82] The UK Former Foodstuffs Processing Association (UKFFPA) estimates a similar figure of 650,000 tonnes annually. These volumes include primarily bakery items, pasta and breakfast cereals, dairy products, fruits and vegetables, sauces and savoury snacks. They may end up in the animal food chain because they are leftover or excess to requirements, or are unsuitable for sale. This could be, for example, because of production errors (incorrect shaping, flavouring or labelling), expiration past sell-by date, logistical challenges of daily delivery and surpluses from festivities or events (Christmas, Easter etc). WRAP's food material hierarchy states that food surplus should be first redistributed for human consumption, and only then diverted to animal feed.[83] Use as animal feed keeps surplus within the human food chain, albeit at lower efficiency than direct consumption, and prevents it from becoming classified as food waste.

TERMINOLOGY

FOOD SURPLUS

Food materials that are leftover or excess to requirements at different stages of the food value chain. The term is usually used to refer to materials that were suitable for human consumption. This is distinct from **food by-products** which are secondary products produced during the processing or manufacture of a primary food product, for example spent brewers grains, or wheat bran from flour milling.

FOOD WASTE

Food that has been, or is intended to be, disposed of - for example by incineration, landfill, composting or anaerobic digestion. These volumes comprise both materials that could have been consumed by humans and those that are inedible to humans.

FORMER FOODSTUFFS

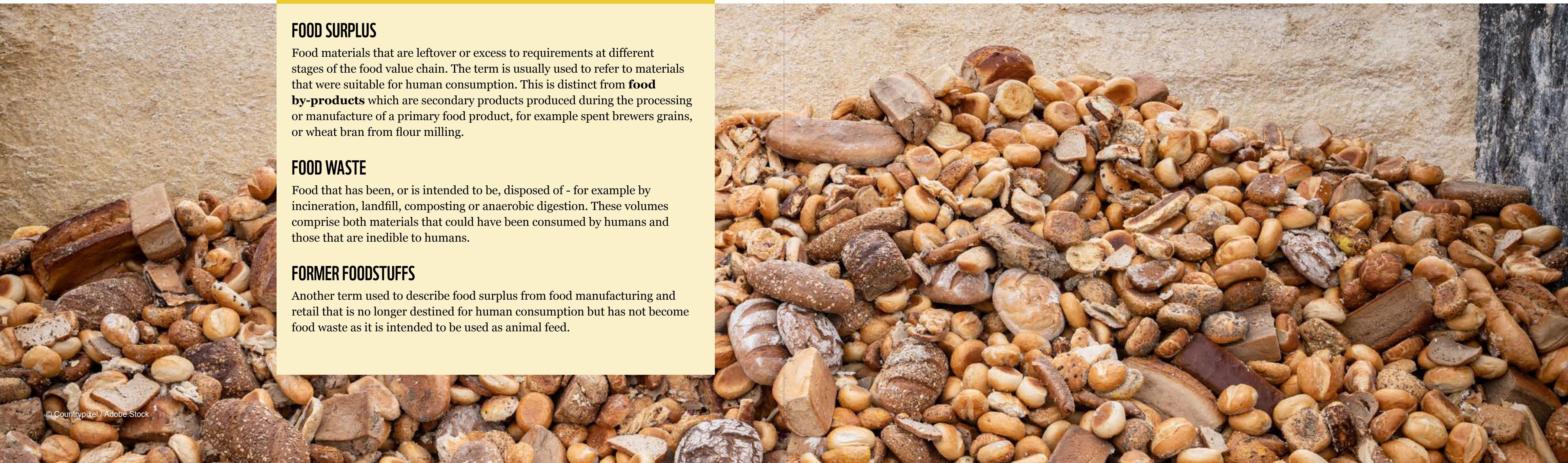
Another term used to describe food surplus from food manufacturing and retail that is no longer destined for human consumption but has not become food waste as it is intended to be used as animal feed.

THE LAW PROHIBITS THE USE OF MOST FOOD WASTE IN ANIMAL FEED

Whatever the true figure for food surplus ending up in the current feed supply chain, it is the case that most food not consumed by humans ends up as waste - in 2018, food waste was estimated at a total of 9.5m tonnes. Waste is generated at every stage in the supply chain, but both households and farms are major sources, alongside relatively smaller contributions from manufacturing, hospitality and food service, and retail. Manufacturing is the next largest source (16%), then hospitality and food service (12%) and retail (3%).[84] Around 70% of this was food intended for human consumption (i.e. edible) and 30% was made up of parts that are inedible to humans. This could represent a significant opportunity for increasing the proportion of LOC inputs to animal feed, as livestock animals (particularly pigs), are well suited to processing leftover food.

> **BAKERY ITEMS AND FRUIT AND VEGETABLES TOGETHER ACCOUNT FOR 80% OF THE FOOD SURPLUS USED IN ANIMAL FEED.**

However, regulations mean that this opportunity is currently heavily circumscribed. Legal limitations on feeding food surplus to animals was introduced in the wake of the BSE crisis to reduce the risk of disease transmission to humans via the consumption of animal products. The regulations are designed in effect to prevent the inclusion of most animal products - such as fresh or cooked meat or fish, gelatine from ruminants, and unprocessed milk or eggs[85] - in animal feed supply chains, with a small number of carefully controlled exceptions. The consequence is that the vast majority of food currently wasted cannot be used for animal feed, as it is unsegregated and therefore may contain prohibited animal products. The former foodstuffs that do go into animal feed are usually from carefully segregated supply chains, and include bakery and confectionary products that do not contain meat, fish or shellfish; cooked or treated milk or milk products, egg or egg products; and animal fats and fish oils[86]. Currently, bakery items and fruit and vegetables together account for 80% of the food surplus used in animal feed.[87]



RELATIVELY LOW RISK CHANGES COULD UNLOCK MORE FEED FROM MANUFACTURING AND RETAIL

Under current laws, WRAP estimates that there is potential to increase animal feed from food not sold as intended at retail and manufacture by only 194,000 tonnes. Manufacturing makes up the majority of this as segregation of products is easier compared to retail. However, changes to the law could expand this potential considerably. WWF's Future of Feed report (2021) identifies unsegregated retail and manufacturing surpluses and bakery or confectionary products containing animal products as the most promising streams of food surplus that could be permitted for use as future substrates for insect rearing, based on the estimated volume and security of supply of these materials, the likely nutritional profile of the materials, and the risk of contamination. It is likely that a similar logic would apply to surplus fed directly to livestock. Extension of current processing methods such as treatment with heat, pressure and acids, which reduce the potential for transmission of disease pathogens, might be applied in order to reduce risk.[88] The addition of these material streams to those currently allowed is estimated to triple the volume of available substrates (Table 8).

The great bulk of food waste, however, is highly mixed with little potential for segregation (e.g. household food waste). As well as disease risks from animal products, there is also a higher risk that foods disposed of in food waste will be decomposing, mouldy, toxic or contaminated with other materials. And there are logistical challenges to using food waste for feed including variability in availability and nutritional value, as well as high processing costs.[89] Nonetheless, historically, mixed food waste has been used to feed pigs, particularly, and this is still common practice in Japan, for instance, for certain mixed food waste streams.[90] In the Japanese system, there are still procedures and controls in place, including that no animal based products are fed to ruminants, but the system allows food waste from catering to be processed through heat treatment, becoming a valuable ingredient in compound feeds for both pigs and poultry. Feedback Global's 'Pig Idea' campaign has argued that up to 2.5m tonnes of surplus food from manufacturing, retail and commercial catering could be fed to pigs.[91] Estimates at an EU level suggest that such policies could result in a 21.5 % reduction in the land used on behalf of EU pork production, saving 1.8m hectares of agricultural land globally that is currently being used to produce feed.[92]

Table 8 **VOLUMES OF SUBSTRATE POTENTIALLY AVAILABLE FOR ANIMAL FEED FROM CURRENTLY PERMITTED SUBSTRATE STREAMS AND FROM MOST VIABLE ADDITIONAL SUBSTRATE STREAMS**

SUBSTRATE	VOLUME (000 TONNES, PROJECTED FOR 2025)
Vegetable surplus	614
Bakery surplus (no animal by-products)	138
Total of currently permitted substrate streams	752
Food surplus (retail)	338
Food surplus (manufacturing)	909
Bakery surplus (with animal by-products)	512
Total of possible additional substrate streams	1,759
Grand total of current plus potential additional substrate streams	2,511

Source: WWF, ADAS, and Michelmores, 2021[93]

> **UP TO 25% OF FOOD PURCHASED BY CONSUMERS IS WASTED. THE IMPETUS SHOULD BE TO REDUCE THIS, WITH DIVERSION TO ANIMAL FEED BEING A SECONDARY CONSIDERATION.**

REDUCING WASTE IS THE FIRST PRIORITY

In considering the potential for greater proportions of animal feed to be derived from food waste and surplus, it is important to state that much of this exists due to undesirable inefficiencies within the current food system. The equivalent of between a fifth and a quarter of all food purchased by consumers is wasted every year.[94] The impetus therefore should primarily be on reducing this volume, and the UK is committed to halving its per capita food waste by 2030[95] as part of our commitment to the United Nations Sustainable Development Goal 12.3.[96] The most efficient use of excess food produced for human consumption and edible by humans is that it should be consumed by humans directly. This could include, for example, redistribution via food banks and charities, or schemes such as the Company Shop.[97] Diversion to livestock should be a secondary consideration, even though it is more desirable than disposing of food as waste via composting, anaerobic digestion, incineration or landfill. Accepting that redistribution for human consumption will not always be possible, however, and given the large volumes of food waste currently generated, there should still be potential to increase the current contribution of food surplus and waste to animal feed.

© Pixel-Shot / Adobe Stock

Figure 10

SUMMARY OF OPPORTUNITY COST OF FEED INPUTS TO UK LIVESTOCK

Grass (including hay and silage) is shown in green, low opportunity cost in blue, high opportunity cost in orange and other in grey. Based on GLEAM-i data

© Sam Hobson / WWF-UK

CHAPTER 4 > ALLOCATING LOW OPPORTUNITY COST FEED

The previous sections have described what low opportunity cost feed is, how much low opportunity cost feed is present in UK animal feed, and the opportunities and constraints around expanding this - particularly for grass and food surplus and waste. Critical to understanding the implications of a hypothetical future feed system based primarily around LOC feed, however, is the question of allocation - in short, how should limited LOC feed resources best be distributed amongst different livestock species with varied nutritional requirements? The answer to this question has significant consequences for what a LOC farming system would look like, and what kind of changes to human diet would be entailed. This section explores the current average dietary compositions of different livestock animals in the UK, and to what extent these could change to accommodate more LOC feed.

4.1 THE DISTRIBUTION OF LOW OPPORTUNITY COST FEED IS UNEVEN ACROSS LIVESTOCK SPECIES

For the purposes of this paper and notwithstanding the caveats in the above sections, we here adopt a simplified low opportunity cost framework in order to analyse the inputs to current livestock feed regimes:

Table 9

SUMMARY OF OPPORTUNITY COST STATUS OF FEED INPUTS, AND COLOUR CODES USED IN THIS DOCUMENT.

LOC = low opportunity cost.
HOC = high opportunity cost.

INPUT	Grass	Cereals and other crops	Soy	By-products	Other
OPPORTUNITY COST	LOC	HOC	HOC	LOC	Unclassified
COLOUR CODE	Green	Orange / yellow	Orange / yellow	Blue	Grey

The 'other' category includes vitamins and minerals, oils and fats, synthetic additives and fishmeal. Fishmeal may include edible fish as well as inedible trimmings from fish processing, however it is not possible to disaggregate these inputs. This category is relatively small, however, and does not significantly affect the overall picture.

These categories have then been applied to species-specific livestock feed composition estimates from the UN FAO's GLEAM database, which are based on dry matter weight.[98] The GLEAM data, which, unlike the UK statistics, do include grass and crop residues, show the high variability in dietary composition between livestock species, notably between ruminants and non-ruminants, but also within these groupings. The feed breakdowns provided are based on adult animals, and specific dietary composition will vary depending on life cycle stage and other contextual factors. Data are based on Western European averages but we have selected the farming systems closest to what is typical in the UK.

4.2 RUMINANTS

SHEEP

On average, compared to other livestock species adult female sheep have the highest proportion of low opportunity cost feed in their diets, at 97% in total, including 86% grass and 8% crop residues. According to the GLEAM data only 3% of the diet consists of crops, commonly fodder beet. This adult diet is not typical of lambs, however, which often receive concentrate 'creep feed' including grains and soy whilst still suckling, especially if born before grass conditions are optimal. They may then also continue on concentrate feed after weaning. However, concentrates are more expensive than grass, so the additional nutrition has to be balanced against economic profitability.

CATTLE

Adult meat cattle in the predominantly mixed indoor/outdoor farming systems found in the UK have similarly high percentages of fresh grass, hay and silage in the diet, at 83%, with an additional 6.5% crop residues. By-products make up around 4%, including palm kernel expeller, and sugar and grain processing by-products. The overall percentage of high opportunity cost feed is 6.5%, consisting of fodder beet and maize silage. For dairy cattle the average percentage of grass drops to 75%, and high opportunity cost inputs make up 16.5%, predominantly maize silage, plus fodder beet, grains and a small amount of soy. This reflects the greater amount of time spent indoors on average by dairy cows, as well as a nutritional regime optimised for milk production. Dairy calves receive supplemental feed in order for them to reach the time when they can start producing milk more rapidly. Whilst these are average figures, feed ratios will vary for specific production systems, from 100% grass (including silage and hay when not grazing) in certified pasture-fed farms, to very low proportions of grass in intensive dairy units.

Figure 11
DIET COMPOSITION FOR ADULT SHEEP REARED FOR MEAT

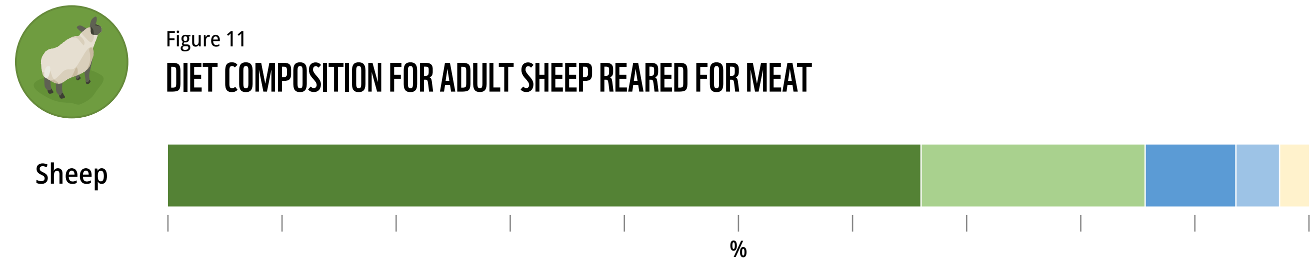
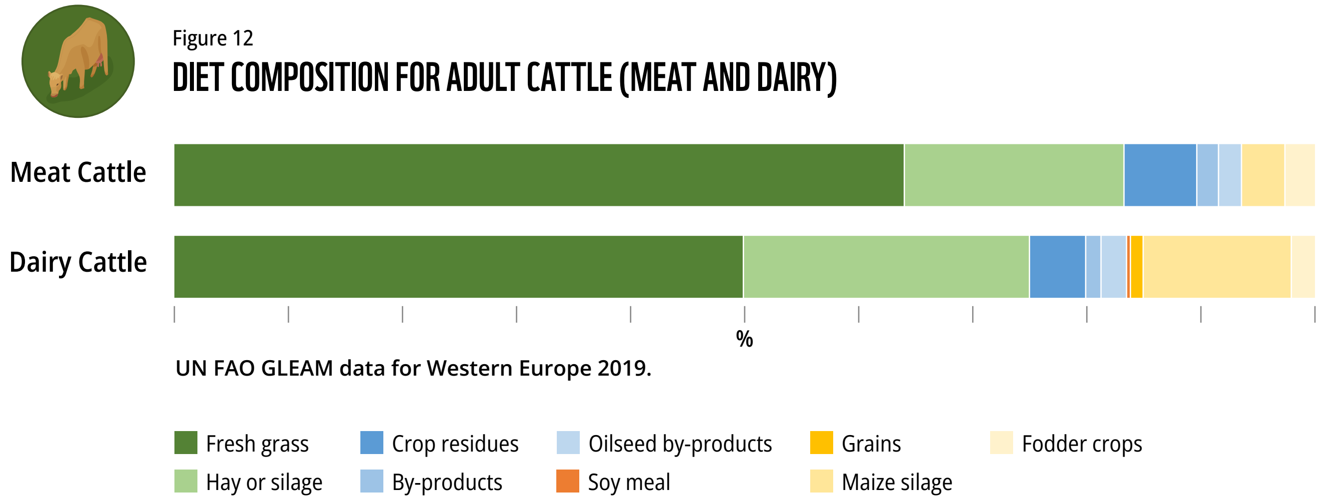


Figure 12
DIET COMPOSITION FOR ADULT CATTLE (MEAT AND DAIRY)



UN FAO GLEAM data for Western Europe 2019.

"FOR UPLAND AND MARGINAL FARMS, FOCUSING ON NATURALLY AVAILABLE GRASS HAS BEEN FOUND TO INCREASE PROFITABILITY

MOVING TOWARDS A LOW OPPORTUNITY COST FEED REGIME FOR RUMINANTS

For ruminants, the two key pathways in transitioning towards a low opportunity cost feed regime would be increasing the proportion of grass in the diet - where this is appropriate within the context of other land use priorities including nature restoration - and the replacement of grains and soy with by-products blended to produce satisfactory results for animal nutrition. Increasing the proportion of grass in ruminant diets is a much discussed topic, and the UK is well suited to grass-based diets given our extensive pastureland. Van Hal et al (2019) model beef cattle under a LOC feed system as consuming 98% grass with only small inputs of feed based on by-products and food surplus. 100% pasture-fed systems for meat cattle and sheep are growing in popularity, albeit still niche overall.[99] Moving towards higher proportions of grass, or even completely pasture based diets would entail accepting slower growth rates and higher methane emissions per animal, due to the lower digestibility and nutrient density of roughage.[100] However, this would not necessarily always imply lower economic returns, with grass that is directly grazed by livestock the cheapest source of feed for UK agriculture,[101] and savings to be made against the cost of concentrate feed. For upland and marginal farms, focusing on naturally available grass (i.e. without artificial fertilisers) as the prime source of nutrition has been found to increase profitability through significant savings on variable costs.[102]

Dairy systems, which increasingly rely on higher rates of cereal and soy inputs, and have a greater proportion of indoor housing, are more challenging. Milk yields from 100% grass-based systems are lower, and have more marked seasonal patterns than concentrate regimes, with declines in milk production in the winter when animals are fed hay or silage, making these systems potentially less economically viable at scale. Dairy cattle in a LOC feed system are likely to therefore have to rely on higher proportions of by-products replacing current soy and cereal inputs. Most by-products have a very different nutritional profile compared to grains, with lower starch content and higher fibre content. Wheat, for example, is 70% starch and 3% fibre compared to wheat by-product feed, which is 23% starch and 10% fibre. Despite this, however, a number of studies suggest that replacement can occur without detrimental impacts on milk yield,[103] even though in one case cows had substantially different nutritional intake under the replacement diet.[104] One recent study demonstrated a milk yield increase when dairy cows were fed with a rapeseed meal based feed rather than soya meal, which was attributed to the superior amino acid profile of rapeseed compared with soya.[105]

4.3 MONOGASTRICS

PIGS

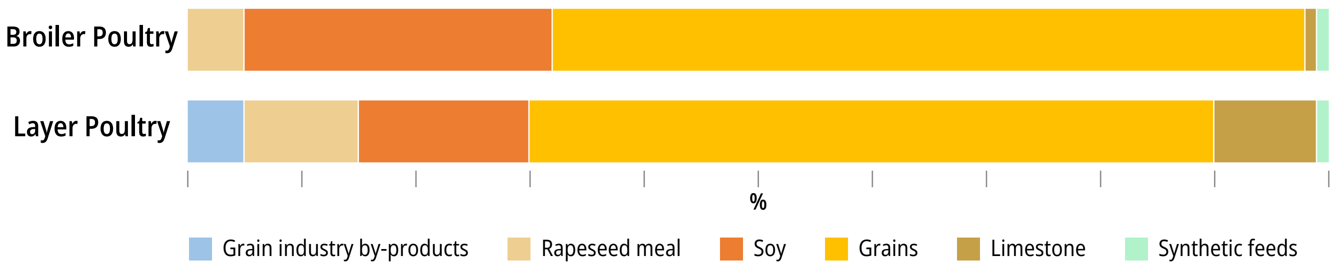
Compared to ruminants, monogastric animals reared in the UK have a far lower proportion of low opportunity cost feed. Due to their digestive physiology, pigs and poultry require relatively high protein in their diet and, unlike ruminants, are limited in their ability to ferment large quantities of roughage.[106] 'Industrial pigs' - i.e. reared indoors in pens - which are now the majority of UK pig production, have on average only 5% low opportunity cost feed, consisting of food industry by-products. Diets may be up to 35% soy and 49% grains. Pigs reared in 'intermediate' - i.e. outdoor reared - settings have around 23% LOC feed including grain industry by-products and crop residues. However, the majority of the diet consists of soy and grains, including wheat, maize, barley and legumes. Feeds also include fishmeal, and synthetic additives such as amino acids.

POULTRY

For poultry, the majority of which are reared in industrial systems in the UK, the picture is similar to pigs. Laying hens have around 15% low opportunity cost feed, made up of by-products including oilseed meal, with the remainder predominantly grains and soy. Their diets can also be supplemented with calcium carbonate (limestone, or crushed oyster or mussel shells) in order to make eggshells more effectively. The diet of broilers is up to 93% high opportunity cost ingredients, with 5% oilseed meal the only by-product component listed by GLEAM-i.

Figure 13

DIET COMPOSITION FOR PIGS (INDUSTRIAL AND INTERMEDIATE SYSTEMS)



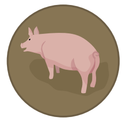
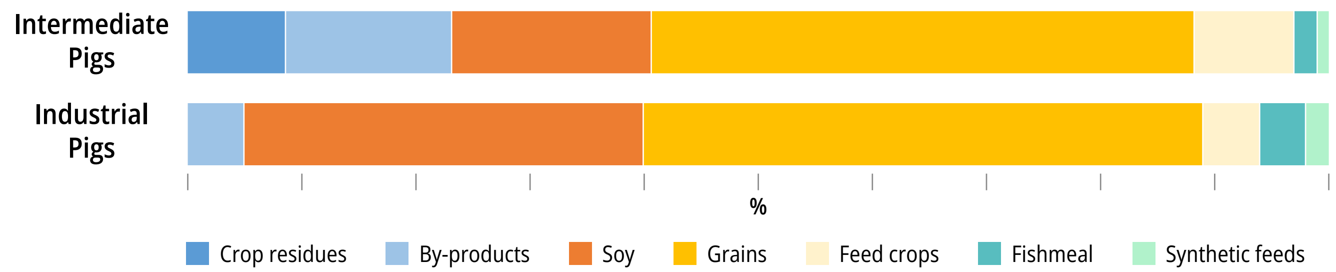


Figure 14

DIET COMPOSITION FOR POULTRY (BROILERS AND LAYERS)



UN FAO GLEAM data for Western Europe 2019.

MOVING TOWARDS A LOW OPPORTUNITY COST FEED SYSTEM FOR MONOGASTRICS

In pig and poultry diets, the key challenge for a circular feed system is replacing cereals and soy, which make up 70-90% of inputs on average. Industrialised systems optimised for rapid growth and high outputs now predominate in the UK, with 7 out of 10 of the UK's largest poultry farms housing more than 1m birds, and pig farms housing up to 23,000 animals.[107] There are almost 1500 Integrated, or Intensive, Poultry Units (IPUs) in the UK, housing more than 40,000 birds each, including 575 mega poultry farms housing at least 125,000 broilers or 82,000 layers.[108] In these industrialised settings, livestock feed is highly calibrated for maximum growth rates, and fitted to particular life cycle stages. This makes the nutritional variability of LOC ingredients, and limitations on suitability, a limiting factor on their inclusion in diets, for poultry in particular. There are examples of commercially viable 100% LOC feed poultry systems, such as Kipster in the Netherlands, which uses a feed produced by Nijsen based on bakery waste and surplus. However, it is unclear how easily the use of by-products in this relatively small scale high-welfare setting with 24,000 layers could be translated to the larger industrialised productivity-driven systems that now predominate in the UK. The most promising avenue for poultry is the conversion of food waste to standardised high protein insect meal that would meet many of their nutritional requirements.[109] A recent WWF-UK report estimated that by 2050 insect meal could replace over half a million tonnes of soy in animal feed by 2050, with poultry one of the main potential beneficiaries of this innovation.[110]

Opportunities to increase LOC feed for pigs are more immediately promising. Pigs are by nature omnivorous scavengers with the potential to consume a wide variety of feedstuffs, including wet by-product feeds that are less suitable for poultry. Traditionally pigs were fed on pigswill - food waste and scraps - which was legal in the UK until 2001. With a change in the law, including additional safeguards to protect human health, this could again be possible. Policies favouring outdoor-reared pigs could also help shift feed profiles away from those found in highly calibrated industrial systems, as well as promoting greater animal welfare. In Japan, the use of ecofeed manufactured from food waste from manufacturing and retail grew more than four-fold between 2003 and 2017.[111] In experiments a liquid ecofeed containing 6% soy but no cereals was found to produce comparable results in terms of daily gain compared to a control feed, and higher levels of intramuscular fat.[112]

In general, using by-products in place of cereals and soy is likely to entail greater complexity, as they have far greater nutritional variability, may have limited or sporadic availability or require specialist storage arrangements, and require greater mixing and blending to achieve desired nutritional outcomes. The Japanese ecofeed experience has shown, however, that processes are able to adapt and innovate where there are policies in place to promote use of food waste. Farmers may also have to adapt their systems and practices to use feeds with different qualities and delivery mechanisms.

4.4 OPTIMAL ALLOCATION OF LOC FEED BETWEEN SPECIES

This section has demonstrated the differing characteristics of each of the key UK livestock species, their production systems and nutritional requirements, and their suitability for utilising different sources of low opportunity cost feed. How available LOC feedstuffs would be allocated to the different species has significant implications for the mix of animals and productivity of a theoretical low opportunity cost feed system. An optimal allocation of LOC feed resources to produce the greatest nutritional value for human food would probably look very different to today. Whilst now the UK's livestock population is dominated by poultry birds consuming diets heavy in cereals and soy, poultry are actually the worst suited to utilising low opportunity cost feed. Many academic models of optimised LOC feed systems therefore reduce poultry numbers considerably.[113] Where poultry are included, they are best suited to consuming cereal processing by-products and oilseed cake and meal.

Where increased quantities of food waste and surplus are assumed to be available due to legislative changes, then compared to a no-food-waste scenario, models include relatively higher numbers of pigs, the species best suited to converting this into nutrition. For ruminants, grass is the preferred primary nutritional input, supplemented with by-product feeds at key growth stages. In many models there is preference for dairy over beef cattle as they are more efficient converters of grassland to protein, with meat from dairy animals providing beef in addition to milk.[114] None of the prominent academic models include sheep, which are important in the UK context - this represents a future research need.

The next section explores the potential consequences of a LOC feed system for human diets.

CHAPTER 5 > COULD A LOC SYSTEM FEED THE UK?

5.1 LIVESTOCK FED ON LOC FEED COULD PRODUCE UP TO 31g OF ANIMAL SOURCE PROTEIN PER PERSON PER DAY

For this project we reviewed a variety of academic papers that model the potential amount of protein from animal source food (ASF) that could be obtained from livestock production relying entirely on low opportunity cost feed. It is noted that protein is only one metric of a healthy diet, and that wider modelling of caloric and micronutrient intakes from alternative diets would also be required. However, for the purposes of this paper, protein is used to understand at high-level the potential viability of a low opportunity cost system to underpin human nutrition. A summary of papers analysed is provided in Appendix 2. Estimates range from 7 g/capita/day (van Kernebeek, 2016;[115] Smil, 2014[116]) to 31 g/capita/day (van Hal, 2019)[117] of animal derived protein. This variability is driven by significant uncertainties around assumptions as well as lack of consistency around some of the key parameters of low opportunity cost feed, reflecting some of the underlying definitional complexity discussed in Section 2. Some of these differences between studies are summarised below:

Table 10 KEY ASSUMPTIONS OF LOC FEED SYSTEM MODELS

DEFINITION OF LOW OPPORTUNITY COST FEED	Some or all of the following may be included: • Food waste and surplus • By-products and or co-products • Crop residues • Some studies include all pastures, others only marginal grasslands
SCALE AND LOCATION	Global or national scale. Though no national level analysis has been carried out for the UK, many studies are Western European. This has implications for diet, livestock types and production systems.
SOURCE DIET	Food waste and co-product availability depends on population diet. Diets used in most of the literature can be categorised as one of: • Current (national, EU or global) • Vegan (fully plant-based or current plant-based foods only) • Nutritional (e.g., from government recommendations) • Optimised (to minimise land use e.g., through modelling (Kernebeek, 2016) or assumptions to increase co-product value (Elferink, 2008; Van Zanten, 2016)[118]
LIVESTOCK TYPES	Some studies modelled only one or two livestock species, whilst others included a combination of meat and dairy cattle, broiler and egg laying chickens, pigs and fish. No studies reviewed included sheep.
CONVERSION FACTOR ASSUMPTIONS	For example, livestock number per unit area of land, growth rates and protein conversion efficiencies. National level studies often model highly domesticated species bred for efficient protein conversion from quality forage, while global studies base calculations on species optimally reared at low intensities on low quality forage.

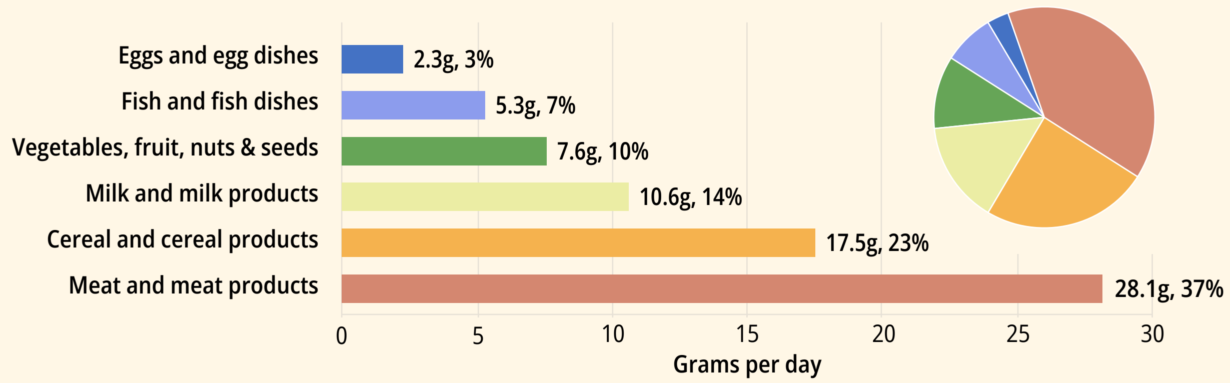
Overall, we conclude that the lower end estimates of this set of studies can be assumed to be overly conservative for the UK. These are often based on global averages (7g, Smil, 2014; 9g, Schader, 2015[119]) rather than European data (e.g., Roos, 2016[120], 2017[121]; Elferink, 2008)[122], assuming lower availability of potential LOC feed than is the case in wealthier, more wasteful western societies. Further, global studies differ in the assumptions of their output systems. Tropical cattle, optimally reared at low intensities on low quality forage are often used as the model system upon which protein conversion efficiencies, growth rates and grazing densities are based. Smil's 2014 study estimating ASF protein availability of 7g / capita/day, for example, uses low efficiency tropical breeds, global averages of co-product and food waste availability, and does not model dairy and lamb, which are major constituents of the UK livestock system. By comparison, studies based on western agricultural systems (e.g. Van Hal, 2019) assume highly domesticated breeds bred for optimal growth and protein conversion efficiency.

The upper range of estimates from 20-31g in general are the best fit for the question that this paper is asking - what could be the potential of this kind of system in the UK? Estimates under 20g tend to exclude one or other key category of potential inputs, such as food waste, or include a constraint such as only allowing marginal pastures or using a limited number of livestock species. Van Hal et al's upper estimate of 31g is based on a model that includes all available grassland (not just marginal), by-products, and 35% of food waste used for animal feed. The modelled system supports 78% fewer pigs, 98% fewer laying hens but 9% more dairy cattle for the EU as a whole. In the model broilers and beef cattle are excluded entirely. For the UK specifically, the model suggests an optimal livestock population of 10 million pigs (twice as many as today) consuming mostly oilseed by-products and food waste; and 3 million dairy cattle consuming mostly grass plus a small percentage of supplemental oilseed and cereal processing by-products. If food waste is excluded, the optimisation model removes pigs entirely from the system and allocates more by-product based feed to dairy cattle. Perhaps surprisingly, this results in only a 3% reduction in animal source protein production, to 30g /person/day.

5.2 A LOC FEED SYSTEM IN THE UK COULD POTENTIALLY MEET NUTRITIONAL RECOMMENDATIONS

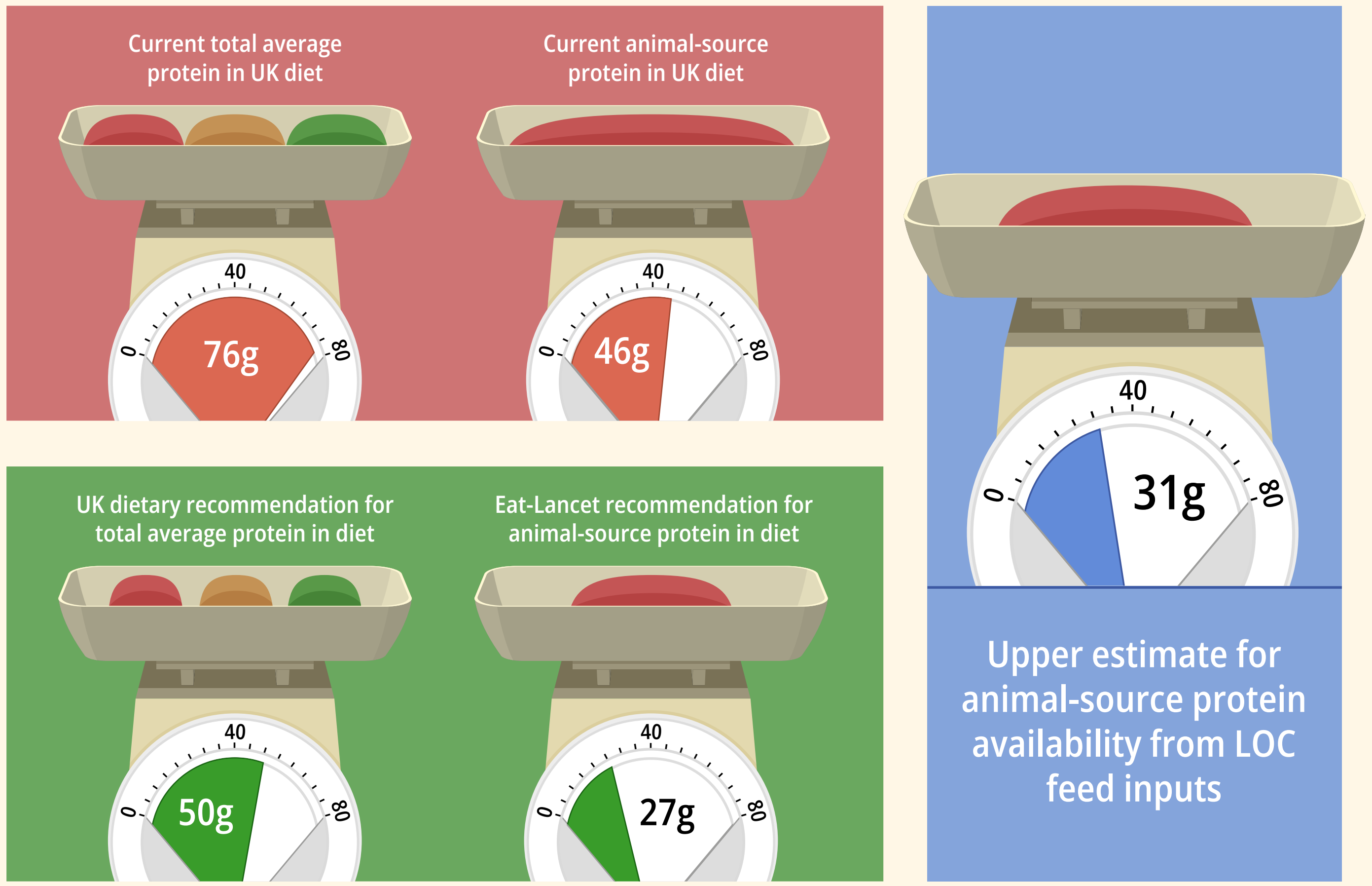
If we assume for a moment this upper estimate could be realised, what does 31g of animal source protein represent? Comparing the figure against nutritional recommendations suggests that it could make a substantial contribution. 31g exceeds the overall ASF protein recommendation of the globally recognised EAT-Lancet Commission Planetary Health Diet, which equates to around 27g.[123] This amount of protein would also provide 60% of the UK's average recommended total dietary protein intake from both animal and plant sources, of 50g per person per day.[124] The remaining 40% - or 19g - of protein would be easily supplied by plant-based foods given that the average UK diet already contains 25g of protein from plant sources, mostly cereals (see Figure 15 below).[125]

Figure 15
SOURCES OF PROTEIN IN THE DIET OF UK ADULTS[126]



This suggests that relying solely on low opportunity cost feeds for livestock might not entail the need to very significantly raise the production and consumption of plant-based proteins, at least on the basis of overall protein amount. The fundamental reason for this is that in the UK we currently considerably over-consume protein compared to dietary recommendations. On average, dietary recommendations for protein are 56g per day for men and 45g for women, whilst the actual consumption figures are 88g (57% higher) and 64g (42% higher), respectively. Despite this observation around the sufficiency of overall protein volume, there may still, however, be a need to increase the diversity and scale of plant protein from non-cereal sources (e.g. nuts, legumes) in the diet, to ensure nutritional completeness.

Table 11
CURRENT AND RECOMMENDED PROTEIN IN DIETS, PER PERSON PER DAY



Whilst animal-source protein in the diet would decline overall by 33% in a 31g scenario, this would be a smaller drop in meat and dairy consumption than the 50% already suggested by the Eating Better Alliance. The actual composition of animal protein sources would need to differ substantially from today, however, and from most dietary guidelines. For example, EAT-Lancet recommends the consumption of higher quantities of chicken meat (29% of ASF protein) compared to beef and pork (13%), but because low opportunity cost feeds are less suitable for poultry, an optimised LOC system would produce mainly dairy-beef, milk and pork.[127] These alternative configurations would need to be studied to assess their health implications, especially since many guidelines have emphasised the need to reduce red and processed meat consumption (the latter of which is often pork in the form of ham).

© Joseph Gray / WWF-UK

CHAPTER 6 > CONCLUSIONS

This paper has explored the idea of limiting livestock numbers in the UK to only what could be supplied using feed that doesn't compete directly with human food. This would mean excluding feed inputs that might otherwise be edible by humans, such as cereals and vegetables, as well as inedible feed inputs produced on land that could otherwise have been used to produce crops for people. A livestock system based on low opportunity cost feed would instead prioritise inputs that are not consumed by humans directly, such as grass, by-products from food processing and manufacturing, and food surplus and waste.

This is a radical idea with big implications. Limiting feed to low opportunity cost sources would considerably ease pressure on arable land in the UK and globally, opening up new opportunities for creative and nature-positive land management. It would also massively reduce the number of livestock animals, in one model reducing the UK's headcount of non-poultry livestock from 48m to 13m and eliminating the 187m poultry birds entirely - whilst still providing sufficient animal protein for human health.[128] With these lower numbers, the non-feed environmental impacts of livestock would therefore also be much reduced compared to today. These impacts include greenhouse gas emissions, as well as the eutrophication, water and air pollution associated with high levels of nitrogen, phosphate and ammonia in manure. Exactly how these impacts would be affected is highly sensitive to the assumptions of the optimisation models used to allocate desired numbers of particular species. For example, models that give preference to dairy cattle over those with higher number of pigs would entail a relatively higher GHG footprint due to the greater contribution of ruminants to methane emissions. Overall, however, studies suggest that globally, a livestock system based on LOC feed could reduce overall livestock emissions by 19-50%, nitrogen losses by 40% and phosphorus losses by 46%.[129]

This final section explores the implications and future of the low opportunity cost feed idea, asking what difference the increased availability of land might make, and how future research and policy could promote a shift towards such a system.

6.1 LOWER PRESSURE ON LAND OPENS UP OPPORTUNITIES TO BRING BACK NATURE

By excluding cereal crops from animal feed, up to 1.9m hectares of arable land currently used to feed animals (41% of the UK's utilised cropland) could be freed up. Some of this may be required to grow additional crops for direct human consumption, making up for the lower levels of animal source protein available. As a rough indication of what this might look like, if we were to double the current amount of non-cereal plant-based protein in UK diets to 15g, and assume for the sake of argument that the additional 7.5g per capita/day were provided entirely by fava (broad) beans, this could be produced on roughly 650,000 ha, or one third of the newly available land.[130] Assuming 31g of animal source protein were produced by livestock fed on low opportunity cost feed, this additional 7.5g, alongside the 25g of plant protein in the existing UK diet, would easily exceed the UK's dietary guidance of 50g protein per person per day, even allowing for some wastage or overconsumption.

Assuming, then, that the majority of land would not be required to grow new plant-based nutrition, the critical benefit for nature could be the opportunity to enable a lower intensity 'land-sharing' approach to farming, with regenerative agriculture at its heart. The extra slack in the system created by not growing crops for animals would allow for a landscape in which an interconnected patchwork of crops, livestock and nature are designed for people, biodiversity and resilience rather than maximum yield per hectare. This could be a significant contribution to achieving both carbon sequestration and biodiversity conservation in the UK, one of the most nature-depleted countries in the world.[131] In this future, nature and productive activities go hand in hand, with both supporting farmer livelihoods and rural communities. Some of the arable land no longer needed for livestock feed production might be used directly for nature restoration where relevant to local nature priorities and ecological connectivity strategies. Semi-natural land including biodiverse mixed woodland and grassland could also incorporate low density grazing and the sustainable harvesting of timber for construction and fuel. However, the more significant opportunities for large-scale restoration would come largely in marginal upland areas where current grazing produces little food overall. Some loss of grazing land in marginal areas could be offset by increases in temporary grassland within an expanded area of lowland agroecological mixed farming.

Using only low opportunity cost feed would also release pressure on land outside of the UK. A proportion of this would relate to imported cereals - this is not quantifiable as the actual percentage of imported cereals used in animal feed is unknown, although we do know that it is relatively low (single digits). The largest impact on land abroad would be around reduced demand for soy meal. Calculations suggest that for the estimated 2.5m tonnes of soy cake and meal in animal feed, the associated land footprint could be around 850,000 hectares.[132] Around 65% of the UK's soy is imported from Argentina, Brazil and Paraguay, which are all high risk countries for deforestation and biodiversity loss, so removing soy from animal feed would reduce land conversion pressure.

6.2 RESEARCH, INNOVATION AND POLICY DIRECTIONS

A livestock system based on low opportunity cost feed is a big idea that challenges many assumptions about how we should produce food. This final section summarises some of the big picture takeaway recommendations for moving this idea forward.

1 BE CLEAR ON THE NEED FOR 'LESS AND BETTER' MEAT AND DAIRY IN THE UK

Despite overwhelming evidence that reducing meat consumption is essential for achieving sustainability goals including climate change, this is still not reflected in the UK's official net zero strategy. It is vital to keep making the argument, emphasised in WWF's Livewell reports,[133] that rebalancing the UK's average dinner plate substantially in favour of plants, and reducing all meat, not just red meat, will be needed to ensure a sustainable, healthy future. Significant investment and policy innovation needs to be directed towards driving behavioural change. This consumption shift can be accomplished at the same time as prioritising 'better' production systems that value nature, animal welfare, and farmer livelihoods. Food businesses and government have a key responsibility to provide farmers with the economic and policy support that will enable a just transition to a 'less and better' system to occur.

2 NORMALISE A MULTI-METRIC APPROACH TO SUSTAINABLE FOOD POLICY

An opportunity cost lens on sustainability shows that it is essential that food policy takes a systemic, multi-metric approach including land, water and biodiversity, and adopts a nuanced approach to the relative balance of methane and CO_2 emissions. The compelling simplicity of measuring average greenhouse gas emissions per gram of meat or protein produced has been remarkably effective in spurring debate on the role of livestock in food systems, yet it masks a far more complex and multi-layered picture. With average emissions per gram of protein four times higher than pork and six times higher than chicken meat,[134] beef has become a target for climate activism. However at the same time, increases in poultry production and consumption in the UK have been driving land use and land use change for high opportunity cost feed production. A low opportunity cost feed framework turns this on its head, highlighting the pressures that intensive poultry places on the environment worldwide and their limited potential to utilise low opportunity cost feeds, and suggesting that a significantly reduced cattle herd could play a key role in future climate-friendly food systems. Ultimately, this demonstrates the need to bring these multiple perspectives into dialogue rather than relying on any single sustainability indicator.

3 BRING LOW OPPORTUNITY COST FEED INTO MAINSTREAM POLICY DISCUSSION AND CORPORATE TARGETS

Continuing on from this point, there is a risk that government and corporate policy becomes increasingly dominated by overly simplistic climate-focused metrics, especially as net zero targets become ever more pressing. Ideas around replacing cereals and soy in livestock feed with low opportunity cost ingredients are currently largely absent from these discussions. Indeed, there is a risk that climate policy pushes cattle feed, for example, away from grass due to its associations with higher methane emissions on a per-animal basis, and towards more easily digestible higher opportunity cost feeds instead. However, a low opportunity cost feed system could be an important part of building a sustainable and resilient food sector, reducing reliance on global commodity markets and artificial fertilisers, and building instead on the skills and knowledge of farmers to deliver regenerative agricultural solutions. Incentives such as Environmental Land Management Schemes (ELMS) should promote agroecological practices such as the inclusion of grass and livestock in arable rotations. Raising the profile of low opportunity cost feed in corporate settings could spur innovations such as Nijsen's 100% by-product poultry feed in the Netherlands. Bringing LOC feed to the forefront of national policy discussions in forums such as the National Food Strategy and with players like the Committee on Climate Change and National Farmers Union is also needed to put the opportunity cost of feed more squarely on the table.

4 PROMOTE INNOVATION IN LOW OPPORTUNITY COST FEED

Technological innovations already under development offer multiple opportunities that could transform the availability and utilisation of low opportunity cost feed inputs to the livestock sector, and accelerate a transition away from cereals and soy for non-ruminants. Whilst current availability of low opportunity cost feed inputs tends to favour ruminant and pig production, technological solutions could facilitate the production of high protein LOC concentrate feed well suited to poultry, allowing for a more balanced mix of livestock species to be produced. These innovations include insect systems, which can transform highly variable-quality food waste into a standardised, easily fed, high-protein meal. Microbial technologies already being commercialised promise to be even more transformative, with the ability to produce proteins based on feedstocks of gases like CO_2, methane and hydrogen. Experimental biorefinery technology allows grass to be transformed into a protein concentrate feed for monogastrics, alongside other products. Seaweed is a promising feedstock that requires no land area to produce, with methane-reducing qualities for ruminants. With adequate investment and government support including enabling policy, research funding and subsidies, these kinds of technologies are potentially scalable to represent a substantial contribution to high-protein, low opportunity cost animal feed. Businesses should seize the opportunity for innovation and work with supply chain actors to share costs and promote R&D.

5 FUND UK-SPECIFIC DATA, RESEARCH AND MODELLING

A potential missing ingredient for getting low opportunity cost feed more effectively into policy is UK-specific research, and hard numbers that model what a low opportunity cost system would look like in context. While an increasing number of modelling studies have looked at both global and European scenarios, the research for this project has shown that these are too generalised to be able to apply to the UK's specific situation. For example, none of the existing studies look at sheep, despite the fact that there are more sheep in the UK than pigs and cattle put together. Models also need to provide a detailed account of the greenhouse gas implications of changes in feed systems and land use - looking at both methane and CO_2. This project has also shown that there are significant gaps in government data collection around livestock feed in the UK - particularly for food surplus and former foodstuffs, imports, inputs fed on farm, and aquaculture - that urgently need to be filled to give a complete picture. Finally, practical on-farm research is needed to establish optimal ways of utilising by-products and waste in animal feeds, and into business models for increasing the use of these inputs in line with demands of both economic and nutritional performance.

6 REVIEW CURRENT REGULATIONS ON THE USE OF FOOD WASTE IN ANIMAL FEED

This report has shown that other countries are able to safely make use of a higher proportion of food waste in animal feed than is currently the case in the UK. Whilst the disease transmission risks from poor practice are real, it is plausible that control measures could provide appropriate safeguards. Food waste has the potential to be a source of low environmental impact feed both directly, for pigs, and indirectly, via insect farming. Reviewing the current rules to assess whether it would be safe and appropriate to make changes would now be a timely intervention given the increasing drive to meet sustainability goals. New technologies such as the use of PCR testing for the presence of ruminant DNA in animal feed may provide additional reassurances. The EU has already softened some regulations around food waste as a feed source - the Food Standards Agency should now be mandated to research whether a partial reintroduction of food waste as a feed source could be feasible, with appropriate safeguards.

APPENDIX 1 > FEED BREAKDOWN METHOD NOTES

COMPOUND FEED

Details of manufactured **compound feed** are provided for the UK by AHDB,[135] and for Northern Ireland by DAERA.[136] These were combined to provide a compound feed breakdown for the UK. This required some assumptions as the categories used in the two countries are only partially consistent. For example, Northern Ireland records no separate data on the use of wheat feed (a by-product of flour milling), but does report on 'other grains and cereals by-products'

INTER/INTRA FARM TRANSFER

Estimates on the details of the inter/intra farm transfer category of feed were provided partially via correspondence with Defra, who gave an indication that this 9.9m tonnes of feed included roughly 1.7m tonnes **wheat**, 2-3m tonnes **barley** and 200-300,000 tonnes **oats**.

We also included in this category the 1.4m tonnes of excess or substandard **potatoes** recorded in Agriculture in the UK as sold for stockfeed (representing 26% of the total volume of harvested production).

Finally, **maize** was calculated based on Defra figures reporting that 228,000 ha of land were dedicated to maize in 2019. We assumed that 30% of this land area was producing maize to produce energy via anaerobic digestion,[137] and that the remaining area had a dry matter yield of 15 tonnes per hectare maize silage (50 tonnes per hectare fresh weight). The resulting 2.4m tonnes of maize silage is consistent with Defra's indication via correspondence that maize represents a significant portion of the inter/intra farm transfer category.

This leaves 1.7m tonnes in the inter/intra farm transfer category **unaccounted for** due to lack of data. It may include forage crops like turnips and kale, silage from other crops e.g. wholecrop wheat or barley, or surplus fruit and vegetable crops. For the purposes of this paper it has been assumed that this additional tonnage is all high opportunity cost, i.e. competes for land with production of food for direct human consumption, although there is a possibility that some of this amount consists of crop residues like straw.

NON-CONCENTRATES

This small category is described by Defra as 'low energy bulk feeds' such as 'brewers and distillers grains, hay, milk by-products and other low energy bulk feeds'.

Based on trade data we have identified imported **brewing and distilling dregs** and imported **sweet potatoes** (not for human consumption) and used a net figure after subtracting anything already accounted for in compound feed.

This leaves 411,000 tonnes **unaccounted for**, which has been treated as low opportunity cost based on the category description provided by Defra.

STRAIGHT CONCENTRATES

Estimates for **cereal crops** (wheat, barley, oats) included in the straight concentrates category were calculated by taking data from Defra's Agriculture in the UK 2019 relating to tonnage of each crop produced for animal feed, and subtracting the tonnage already accounted for in compound feed and inter/intra farm transfer categories.

Maize was accounted for slightly differently as the majority of UK produced maize is fed as silage rather than grain, and is already accounted for under inter/intra-farm transfer. Therefore in the straights category we took the total amount of maize imported to the UK, and subtracted the amount used for human and industrial consumption.[138]

Field beans and **field peas** were accounted for under straights, although they could also arguably have been included under inter/intra farm transfer. Although beans and peas are generally dried and processed, they can also be fed ensiled or as wholecrop (i.e. including stems and leaves) . Field pea tonnage was estimated by taking the total amount recorded as used for feed by Defra minus that already accounted for in concentrates. Field beans were estimated as 80% of the UK's bean production, minus exports, minus that already accounted for in concentrates.

The figure for **soy meal and cake** was arrived at by taking the tonnage of soy meal imported to the UK,[139] adding a figure for soy meal produced in the UK from imported whole beans,[140] and subtracting the tonnage already accounted for in the compound feed statistics. Domestically produced soy meal assumed a yield of 80% from whole beans - the total amount of soy meal was allocated for feed as very little is used for food.

Sunflower cake and meal was calculated as total imports minus the tonnage already accounted for in compound feed.[141] **Rapeseed meal** used the same method, plus assumed that all rapeseed pressed for oil in the UK produced 50% by weight of meal as a by-product, and 100% of this was used for animal feed.

Maize feed and **molasses** were calculated based on tonnage of imports minus that accounted for in compound feeds. For molasses, no data is available on the domestic supply for animal feed, so this is not included.

This leaves 1.6m tonnes of straight concentrate feedstuffs **unaccounted for**. This is likely to include domestically produced by-products for which no data is available, such as molasses (as above), sugar beet pulp, cereal offals and other food industry by-products. As such this 1.6m tonnes have been classed as low opportunity cost for the purposes of this paper.

APPENDIX 2 > COMPARISON OF LOW OPPORTUNITY COST FEED MODELS

PROTEIN (G)	AUTHOR	REGION	INPUT				FOOD WASTE AVAILABILITY	DIET	ANIMAL SOURCE FOOD TYPES					NOTES AND OTHER KEY ASSUMPTIONS
			FOOD WASTE	BY-PRODUCTS	PASTURE	CROP RESIDUES			BEEF	PORK	POULTRY	DAIRY	EGGS	
31	Van Hal 2019	EU	●	●	●		35%	Current plant source	●	●		●	●	Normally distributed pasture quality. Productivity of cattle - 3 levels based on EU systems, e.g. high productivity Dutch dairy cows vs low intensity Irish dairy cows
30	Van Hal 2019	EU		●	●			Current plant source	●	●		●	●	Normally distributed pasture quality. Productivity of cattle - 3 levels based on EU systems, e.g. high productivity Dutch dairy cows vs low intensity Irish dairy cows
27	Van Hal 2019	EU	●	●	●		35%	Current plant source	●	●		●	●	Normally distributed pasture quality. Productivity of cattle - 3 levels based on EU systems, e.g. high productivity Dutch dairy cows vs low intensity Irish dairy cows
27	Elferink et al 2008	Netherlands		●				Current Dutch		●				
21	Van Zanten 2016	Global	●	●	●		10%	Vegan/ optimised	●	●		●		All currently used pasture, even if it has potential to be arable.
20	Van Hal 2019	EU	●	●	●		35%	Current plant source	●	●		●	●	Only marginal pastures.
17	Van Zanten 2016	Global	●	●	●		10%	Vegan/ optimised	●	●		●		Only marginal pastures. Assume all oil = soya. Based on a nutritional diet, but for a given food group (e.g. oil), those with the best co-product utilisation as feed are presumed to be the only crop for this group.
16.2	Elferink et al 2008	Netherlands		●				Current Dutch		●				Assume all oil = soya. This study takes into account the largest streams of food residue from the Dutch food industries, namely the sugar beet industry, the vegetable oil industry and the potato product industry (Potato, sugar beet, molasses and soy by-products only)
9	Schader et al 2015	Global		●	●	●		Optimised, adjusted from FAO 2050 projections	●	●		●	●	Scenario 2 - considering climate change impacts. Food supply before subtraction of food waste at retail and consumption level. For the production level, the quantities of food loss reported in FAOSTAT have been used.
8	Schader et al 2015	Global		●	●	●		Optimised, adjusted from FAO 2050 projections	●	●		●	●	Scenario 1 - not considering climate change impacts. Food supply before subtraction of food waste at retail and consumption level. For the production level, the quantities of food loss reported in FAOSTAT have been used.
7	Van Kernebeek 2016	Netherlands	●	●	●		21%	Optimised	●	●		●		This is an optimisation model (minimum amount of land required to feed the population), not the max protein that could theoretically be produced on the resources available. Includes crops grown for feed, where this is the most efficient.
7	Smil 2014	Global		●	●	●		Vegan	●	●	●			Top down approach from global average diet, waste, which is much less than EU average.
5.6	Elferink et al 2008	Netherlands		●				Current Dutch		●				Only domestic by-products (potato and sugar beet and molasses - excluding soy)

Elferink, E. V. et al. (2008) 'Feeding livestock food residue and the consequences for the environmental impact of meat', Journal of Cleaner Production, DOI:http://dx.doi.org/10.1016/j.jclepro.2007.06.008

Schader, C. et al. (2015) 'Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability', Journal of the Royal Society Interface, DOI:https://doi.org/10.1098/rsif.2015.0891

Smil, V. (2014) 'Eating meat: Constants and changes', Global Food Security, DOI:https://doi.org/10.1016/j.gfs.2014.06.001

van Hal, O. (2019) 'Upcycling food leftovers and grass resources through livestock: Impact of livestock system and productivity', Journal of Cleaner Production, DOI:https://doi.org/10.1016/j.jclepro.2019.01.329

Van Kernebeek, H. R. J. et al. (2016) 'Saving land to feed a growing population: consequences for consumption of crop and livestock products', Int J Life Cycle Assess, 21, pp.677–687, DOI:https://doi.org/10.1007/s11367-015-0923-6

Van Zanten, H. H. E. et al. (2016) 'Opinion paper: The role of livestock in a sustainable diet: a land-use perspective', Cambridge University Press, DOI:https://doi.org/10.1017/S1751731115002694

ENDNOTES

1 See WWF-UK's recent reports 'Riskier Business: The UK's Overseas Land Footprint' (2020) and 'Thriving within our Planetary Means: Reducing the UK's Footprint of Production and Consumption by 2030' (2021)

2 WWF-UK and Tesco (2021) Development of a roadmap to scale up insect protein production in the UK for use in animal feed. Adas. Available at: https://www.wwf.org.uk/sites/default/files/2021-06/the_future_of_feed_technical_report.pdf

3 WWF-UK (2017) 'Eating for 2 Degrees: New and updated Livewell Plates'

4 Willet, W. et al. (2019) 'Food in The Anthropocene: the EAT-Lancet Commission on Healthy Diets From Sustainable Food Systems', EAT-Lancet Commission, DOI:https://doi.org/10.1016/S0140-6736(18)31788-4; Food Farming and Countryside Commission (2021) Farming for Change - Mapping a Route to 2031; Committee on Climate Change (2020) Policies for the Sixth Carbon Budget and Net Zero.

5 Our World in Data (2019) Half of the world's habitable land is used for agriculture. Available at: https://ourworldindata.org/global-land-for-agriculture (Accessed: 1 October 2021).

6 Leip, A. et al. (2015) 'Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity', Environment Research Letters, DOI:http://dx.doi.org/10.1088/1748-9326/10/11/115004.

7 Ruiter, H., J. Macdiarmid, R. Matthews, T. Kastner, L. Lynd and Smith, P. (2017) 'Total global agricultural land footprint associated with UK food supply 1986–2011.' Global Environmental Change-human and Policy Dimensions, 43, pp.72-81.

8 FAO (2016) Environmental performance of animal feeds supply chains: Guidelines for assessment. Rome, Italy: FAO.

9 Alexandratos, N. and Bruinsma. (2012) World agriculture towards 2030/2050: the 2012 revision. Rome, Italy: FAO; Eisler, M. C. et al. (2014) 'Agriculture: Steps to sustainable livestock', Nature, 507(7490), pp.32-4, DOI:https://doi.org/10.1038/507032a.

10 See van Hal, O. (2019) 'Upcycling food leftovers and grass resources through livestock: Impact of livestock system and productivity', Journal of Cleaner Production, DOI:https://doi.org/10.1016/j.jclepro.2019.01.329; van Zanten, H.E. (2019) 'The role of farm animals in a circular food system', Global Food Security, 21, pp.18-22, DOI:https://doi.org/10.1016/j.gfs.2019.06.003.

11 Breewood, H., Garnett, T. (2020) What is feed-food competition? Available at: https://www.tabledebates.org/building-blocks/what-feed-food-competition#FFCBB1 (Accessed: 1 October 2021).

12 T. Garnett (2019) 'Livestock-related greenhouse gas emissions: impacts and options for policy makers' Environ. Sci. Policy, 12(2009), pp.491-503; Röös, E., et al. (2016) 'Limiting livestock production to pasture and by-products in a search for sustainable diets', Food Policy, 58, pp.1-13. DOI: https://doi.org/10.1016/j.foodpol.2015.10.008

13 Fairlie, S. (2010). Meat: A benign extravagance. Hartford, VT: Chelsea Green Publishing; Chapman, A. (2017) Meat, a Benign Extravagance [review] Available at: https://www.greenhousethinktank.org/meat-a-benign-extravagance.html (Accessed: 1 October 2021).

14 Wageningen University and Research (2018) Circular agrofood system. Available at: https://www.wur.nl/en/Dossiers/file/Circular-agrofood-system.htm (Accessed: 1 October 2021); van Zanten, H.E. (2019) 'The role of farm animals in a circular food system', Global Food Security, 21, pp.18-22, DOI:https://doi.org/10.1016/j.gfs.2019.06.003.

15 Breewood, H. and Garnett, T. (2020) What is feed-food competition? Available at: https://www.tabledebates.org/building-blocks/what-feed-food-competition#FFCBB3.2 (Accessed: 1 October 2021).

16 Di Paola, A., Rulli, M. C. and Santini, M. (2017) 'Human food vs. animal feed debate. A thorough analysis of environmental footprints', Land use policy, 67, pp.652-659, DOI:https://doi.org/10.1016/j.landusepol.2017.06.017.

17 Cassidy, E. S., West, P. C., Gerber, J. S. and Foley, J. A. (2013) 'Redefining agricultural yields: From tonnes to people nourished per hectare', Environ. Res. Lett. DOI: http://dx.doi.org/10.1088/1748-9326/8/3/034015

18 Cassidy, E. S., West, P. C., Gerber, J. S. and Foley, J. A. (2013) 'Redefining agricultural yields: From tonnes to people nourished per hectare', Environ. Res. Lett. DOI: http://dx.doi.org/10.1088/1748-9326/8/3/034015

19 United Nations Environment Programme (2009) The environmental food crisis – The environment's role in averting future food crises.

20 Mottet, A., et al. (2017) 'Livestock: On our plates or eating at our table? A new analysis of the feed/food debate', Global Food Security, 14, pp.1-8. DOI: https://doi.org/10.1016/j.gfs.2017.01.001.

21 Feedback Global (2021) Living well on leftovers: the potential of nutrient recycling to contribute to reduced meat production and consumption, within planetary boundaries. London: Feedback.

22 Mottet, A., et al. (2017) 'Livestock: On our plates or eating at our table? A new analysis of the feed/food debate', Global Food Security, 14, pp.1-8. DOI: https://doi.org/10.1016/j.gfs.2017.01.001.

23 van Zanten, H. E., et al. (2018) 'Defining a land boundary for sustainable livestock consumption', Global Change Biology, 24(9), p4185-4194. DOI:https://doi.org/10.1111/gcb.14321.

24 Fairlie, S. (2019) 'Eating the Platter Clean', The Land Magazine, 24, pp18-24, Available at: https://www.thelandmagazine.org.uk/sites/default/files/Eating%20the%20Platter%20Clean%20-%20webres2.pdf (Accessed: 1 October 2021).

25 WRAP (2016) Guidance for Food and Drink Manufacturers and Retailers on the Use of Food Surplus as Animal Feed, Banbury, UK: Prepared by Anthesis (UK) Ltd. Available at: https://wrap.org.uk/sites/default/files/2020-09/WRAP-2016-05-17-Animal-Feed-Guidance-v1.0-for-publication.pdf

26 WRAP (2016) Guidance for Food and Drink Manufacturers and Retailers on the Use of Food Surplus as Animal Feed, Banbury, UK: Prepared by Anthesis (UK) Ltd. Available at: https://wrap.org.uk/sites/default/files/2020-09/WRAP-2016-05-17-Animal-Feed-Guidance-v1.0-for-publication.pdf

27 Fraanje, W. and Garnett, T. (2020) Soy: food, feed, and land use change, Available at: https://tabledebates.org/building-blocks/soy-food-feed-and-land-use-change (Accessed: 1 October 2021).

28 Soy meal can additionally be used to produce soy flour for human consumption, so could be classed as human edible despite the fact that only 2% of soy meal is used for this purpose.

29 Mottet, A., et al. (2017) 'Livestock: On our plates or eating at our table? A new analysis of the feed/food debate', Global Food Security, 14, pp.1-8. DOI: https://doi.org/10.1016/j.gfs.2017.01.001.

30 Conant, R.T., Cerri, C.E.P., Osborne, B.B. and Paustian, K. (2017), 'Grassland management impacts on soil carbon stocks: a new synthesis', Ecol Appl, 27, pp.662-668. DOI:https://doi.org/10.1002/eap.1473

31 Defra (2021) Convert arable land to permanent grassland, London: Defra. Available at: https://www.gov.uk/guidance/convert-arable-land-to-permanent-grassland.

32 Jiao, H.P. et al., (2014) 'Effect of concentrate feed level on methane emissions from grazing dairy cows', Journal of Dairy Science, 97(11), pp.7043-7053.

33 Based on Defra's (2019) at: https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom (Accessed 1 October 2021).

34 Based on average UK grassland productivity of 7.3 tonnes dry matter per ha.

35 Defra (2019) *Agriculture in the United Kingdom*. London: Defra. Available at: https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom (Accessed 1 October 2021). Data from 2019 is used to avoid any potential anomalies associated with the coronavirus pandemic in 2020.

36 This paper does not discuss fish and aquaculture

37 Ibid. Weight refers to dressed carcase weight - the weight of the partially butchered animal, including removal of internal organs, head, legs etc.

38 Defra (2021) *Structure of the Agricultural Industry*. 'Livestock numbers in England and the UK'. 25 March 2021 Statistical data set. Available at: https://www.gov.uk/government/collections/structure-of-the-agricultural-industry

39 Defra (2020) *Family Food Datasets*. Available at: https://www.gov.uk/government/statistical-data-sets/family-food-datasets (Accessed: 1 October 2021)

40 HM Customs and Excise summarised at Trading Economics (2021) *United Kingdom Imports of Meat & Edible Meat Offal*. Available at: https://tradingeconomics.com/united-kingdom/imports-of-meat-edible-meat-offal (Accessed: 1 October 2021)

41 Zayed, Y. and Loft, P. (2019) *Agriculture: historical statistics,* House of Commons Library Briefing Paper Number 3339. Available at: https://researchbriefings.files.parliament.uk/documents/SN03339/SN03339.pdf

42 British Meat Processors Association, *Imports & Exports, Beef and Veal,* Available at: https://britishmeatindustry.org/industry/imports-exports/beef-veal/ (Accessed: 1 October 2021); British Meat Processors Association, *Imports & Exports, Pigmeat,* Available at: https://britishmeatindustry.org/industry/imports-exports/pigmeat/ (Accessed: 1 October 2021); Peijs, R. (2016) *Self-sufficiency level in UK poultry drops.* Available at: https://www.poultryworld.net/Meat/Articles/2016/6/UK-less-self-sufficient-for-poultry-2821542W/ (Accessed: 1 October 2021).

43 Defra (2019) *Agriculture in the United Kingdom*. London: Defra. Available at: https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom (Accessed 1 October 2021).

44 Defra (2019) *Agriculture in the United Kingdom*. London: Defra. Available at: https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom (Accessed 1 October 2021).

45 Based on dry matter. FAO (2018) Global Livestock Environmental Assessment Model (GLEAM-i). Available at: https://gleami.apps.fao.org (Accessed: 4 October 2021)

46 Defra (2019) *Agriculture in the United Kingdom*. London: Defra. Available at: https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom (Accessed 1 October 2021).

47 Eurostat (2016). Eurostat Farm Structure Survey. Available at: https://ec.europa.eu/eurostat/web/agriculture/data/database (Accessed 4 October 2021)

48 Eurostat (2019). Glossary: permanent grassland. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Permanent_grassland (Accessed 4 October 2021)

49 FAO (2018) Global Livestock Environmental Assessment Model (GLEAM-i). Available at: https://gleami.apps.fao.org (Accessed: 4 October 2021)

50 Defra (2019) *Cattle Farm Practices Survey*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/831119/Cattle_Farm_practices_survey_April_2019-12sep19.pdf (Accessed: 4 October 2021)

51 ADAS, Available at: https://www.adas.uk/News/cattle-and-sheep-welfare-in-the-uk-what-consumers-should-know (Accessed August 2021)

52 Compassion in World Farming (2016) *The Grass is Greener - The Plight of UK Dairy Cows*. Available at: https://www.ciwf.org.uk/news/2016/04/the-grass-is-greener-the-plight-of-uk-dairy-cows-f1 (Accessed 4 October 2021).

53 Compassion in World Farming (2021) *The Scale of intensive indoor livestock farming in the United Kingdom, and the impact of its related sewage disposal regime upon Water Quality in Rivers*. Supplementary material. Available at: https://committees.parliament.uk/writtenevidence/23622/pdf/ (Accessed 4 October 2021)

54 UK National Food Strategy (2021), The Evidence. P53. Available at: https://www.nationalfoodstrategy.org (Accessed 4 October 2021)

55 March, M. D. et al. (2014) 'Current trends in British dairy management regimens', *Journal of Dairy Science,* 97(12): 7985-94, DIO:https://doi.org/10.3168/jds.2014-8265

56 Defra (2019) *Agriculture in the United Kingdom*. London: Defra. Available at: https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom (Accessed 1 October 2021).

57 Bullock, J. M. et al. (2011). *Semi-natural grasslands. In Technical Report: The UK National Ecosystem Assessment, pp162–195.* Cambridge, UK: UNEP-WCMC. Available at: http://nora.nerc.ac.uk/id/eprint/15322/1/N015322CR.pdf

58 ADAS, Available at: https://www.adas.uk/News/new-tools-for-optimising-grass-production (Accessed: August 2021)

59 The term 'unimproved grasslands' is sometimes used for semi-natural grasslands

60 Walker, K. J. et al. (2004) 'The restoration and re-creation of species-rich lowland grasslands on land formerly managed for intensive agriculture in the UK', *Biological Conservation,* 119(1), pp.1-18, DOI:https://doi.org/10.1016/j.biocon.2003.10.020

61 Bullock, J. M. et al. (2011). *Semi-natural grasslands. In Technical Report: The UK National Ecosystem Assessment, pp162-195.* Cambridge, UK: UNEP-WCMC. Available at: http://nora.nerc.ac.uk/id/eprint/15322/1/N015322CR.pdf

62 Le Quéré, C.L. (2020) *Unpacking the Sixth Carbon Budget, The transition for agriculture, land use and waste.* The Climate Change Committee. Available at: https://www.theccc.org.uk/wp-content/uploads/2020/12/Unpacking-the-Sixth-Carbon-Budget-the-transition-for-Agriculture-and-Land-use.pdf

63 UK National Food Strategy (2021), Available at: https://www.nationalfoodstrategy.org (Accessed 4 October 2021)

64 Food, Farming and Countryside Commission (2021) *Farming for Change, Mapping a route to 2030.* Available at: https://ffcc.co.uk/assets/downloads/FFCC_Farming-for-Change_January21-FINAL.pdf

65 Harvey, D. and Scott, C. (2019) *Farm Business Survey 2017/2018, A Summary from Hill Farming England.* Rural Business Research & Newcastle University, Available at: https://www.ncl.ac.uk/media/wwwnclacuk/naturalenvironmentalsciencesschoolof/files/Hill%20Farming%202017%20-%202018.pdf

66 Natural England Research Report *Grazing Livestock in the Uplands.* Available at: http://publications.naturalengland.org.uk/file/62084

67 The Committee on Climate Change (2018) *Land use: Reducing emissions and preparing for climate change.* Available at: https://www.theccc.org.uk/wp-content/uploads/2018/11/Land-use-Reducing-emissions-and-preparing-for-climate-change-CCC-2018.pdf

68 Defra (2019) *Agriculture in the United Kingdom.* Table 4.3. London: Defra. Available at: https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom (Accessed 1 October 2021).

69 Defra (2019) *Agriculture in the United Kingdom.* Table 9.1. London: Defra. Available at: https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom (Accessed 1 October 2021).

70 UK Parliament (2019) *Animal Feed: Imports, Question for Department for Environmental, Food and Rural Affairs.* Available at: https://questions-statements.parliament.uk/written-questions/detail/2019-09-24/290385 (Accessed 4 October 2021)

71 It is not clear how this is represented in the data from Defra

72 Defra (2019) Agriculture in the United Kingdom. Chapter 7. London: Defra. Available at: https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom (Accessed 1 October 2021).

73 Hill, O. (2016) '30% of total English maize crop goes for anaerobic digestion', Farmers Weekly. Available at: https://www.fwi.co.uk/arable/other-crops/30-percent-of-total-english-maize-crop-goes-for-anaerobic-digestion (Accessed 4 October 2021); direct correspondence with Defra.

74 Defra (2019) *Agriculture in the United Kingdom.* Table 7.2. London: Defra. Available at: https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom (Accessed 1 October 2021).

75 UN Comtrade database

76 Boffey, D. (2021) 'EU to lift its ban on feeding animal remains to domestic livestock', The Guardian. 22 June. Available at: https://www.theguardian.com/world/2021/jun/22/eu-to-lift-its-ban-on-feeding-animal-remains-to-domestic-livestock (Accessed 4 October 2021).

77 AHDB (2021) 'UK imports of non-cereal feed ingredients (NCFIs)'. Available at: https://ahdb.org.uk/cereals-oilseeds/trade-data (Accessed 4 October 2021); UN Comtrade database

78 Efeca (2019) UK Roundtable on Sustainable Soya: Annual progress report, 2019. Available at: https://www.efeca.com/wp-content/uploads/2019/12/UK-RT-on-Sustainable-Soya-APR-2019-final.pdf

79 Fraanje, W. and Garnett, T. (2020) Soy: food, feed, and land use change, Available at: https://tabledebates.org/building-blocks/soy-food-feed-and-land-use-change (Accessed: 1 October 2021).

80 Estimates from AIC, from Feed Navigator, Byrne, J. (2019) 'AIC launches new palm oil credit purchase scheme', Feed Navigator. 7 August. Available at: https://www.feednavigator.com/Article/2019/08/07/AIC-launches-new-palm-oil-credit-purchase-scheme (Accessed 4 October 2021)

81 WRAP (2020). Food surplus and waste in the UK - key facts. Available at: https://wrap.org.uk/sites/default/files/2021-05/WRAP-food-surplus-and-waste-in-the-UK-key-facts-jan-2020-update.pdf

82 WRAP's 660,000 tonnes is similar to an estimate of 650,000 tonnes by the UK Former Foodstuffs Processors Association UKFFPA, although it is notable that some of the constituent parts of the UKFFPA's total might better be classified under other categories of inputs - for example 77,000 tonnes are cereal grains, and 30,000 tonnes are by-products of spirits and beer.

83 WRAP (2020). Food surplus and waste in the UK - key facts. pp.3. Available at: https://wrap.org.uk/sites/default/files/2021-05/WRAP-food-surplus-and-waste-in-the-UK-key-facts-jan-2020-update.pdf

84 WRAP (2020). Food surplus and waste in the UK - key facts. Available at: https://wrap.org.uk/sites/default/files/2021-05/WRAP-food-surplus-and-waste-in-the-UK-key-facts-jan-2020-update.pdf

85 Defra and APHA (2019) Guidance: Supplying and using animal by-products as farm animal feed. Available at: https://www.gov.uk/guidance/supplying-and-using-animal-by-products-as-farm-animal-feed#when-abps-are-farm-animal-feed (Accessed 4 October 2021)

86 Defra (2014) Guidance: How food business must dispose of food and former foodstuffs. Available at: https://www.gov.uk/guidance/how-food-businesses-must-dispose-of-food-and-former-foodstuffs (Accessed 4 October 2021)

87 WRAP (2016) Quantification of food surplus, waste and related materials in the grocery supply chain, pp.85. Available at: https://wrap.org.uk/sites/default/files/2020-10/Quantification-of-food-surplus-and%20waste-in-the-grocery-supply-chain_0.pdf

88 Defra and APHA (2019) Guidance: Supplying and using animal by-products as farm animal feed. Available at: https://www.gov.uk/guidance/supplying-and-using-animal-by-products-as-farm-animal-feed#when-abps-are-farm-animal-feed (Accessed 4 October 2021)

89 Sugiura, K. et al. (2009) 'Ecofeed, animal feed produced from recycled food waste', Veterinaria Italiana, 45(3): 397-404, Available at: https://www.researchgate.net/publication/43136371_Ecofeed_animal_feed_produced_from_recycled_food_waste

90 Refresh (2020) Surplus food as animal feed. Available at: https://eu-refresh.org/sites/default/files/06_Karen%20Luyckx%2C%20Jennifer%20David%2C%20Tomoyuki%20Kawashima_animal%20feed.pdf

91 Feedback Global (2018) Feeding Surplus Food to Pigs Safely, Available at: https://feedbackglobal.org/wp-content/uploads/2018/07/Pig-Idea-UK-policy-report.pdf

92 Zu Ermgassen, E. K. H. J. et al. (2016) 'Reducing the land use of EU pork production: where there's swill, there's a way.' Food Policy, 58, pp35-48. DOI:https://doi.org/10.1016/j.foodpol.2015.11.001

93 WWF-UK and Tesco (2021) Development of a roadmap to scale up insect protein production in the UK for use in animal feed. Adas. Available at: https://www.wwf.org.uk/sites/default/files/2021-06/the_future_of_feed_technical_report.pdf

94 WRAP (2020). Food surplus and waste in the UK - key facts. Available at: https://wrap.org.uk/sites/default/files/2021-05/WRAP-food-surplus-and-waste-in-the-UK-key-facts-jan-2020-update.pdf

95 UK Parliament (2021) Food Waste in the UK. Available at: https://lordslibrary.parliament.uk/food-waste-in-the-uk/

96 FAO (2021) Sustainable Development Goals. Available at: http://www.fao.org/sustainable-development-goals/indicators/1231/en/ (Accessed 4 October 2021)

97 The Company Shop Group. Available at: https://www.companyshopgroup.co.uk/ (Accessed 4 October 2021)

98 FAO (2018) Global Livestock Environmental Assessment Model (GLEAM-i). Available at: https://gleami.apps.fao.org (Accessed: 4 October 2021)

99 As of 2021, the Pasture Fed Livestock Association has 127 certified members managing a total of 22,000 ha of pasture for 100% grass fed livestock.

100 The Food Climate Research Network (FCRN) (2017) Grazed and Confused? University of Oxford. Available at https://www.oxfordmartin.ox.ac.uk/downloads/reports/fcrn_gnc_report.pdf

101 AHDB (2021) The Forage First guide. Available at: https://ahdb.org.uk/knowledge-library/the-forage-first-guide

102 Clark, C. et al. (2019) Less is more: Improving profitability and the natural environment in hill and other marginal farming systems. The RSPB, National Trust and The Wildlife Trusts. Available at: https://www.wildlifetrusts.org/sites/default/files/2019-11/Hill%20farm%20profitability%20report%20-%20FINAL%20agreed%2015%20Nov%2019.pdf

103 Ertl, P. et al. (2015) 'Feeding of by-products completely replaced cereals and pulses in dairy cows and enhanced edible feed conversion ratio', Journal of Dairy Science, 98(2) pp.1225-1233. DOI:https://doi.org/10.3168/jds.2014-8810

104 Karlsson, J. et al. (2018) 'Replacing human-edible feed ingredients with by-products increases net food production efficiency in dairy cows', Journal of Dairy Science, 101(8) pp. 7146-7155. DOI:https://doi.org/10.3168/jds.2017-14209

105 Garnsworthy et al. (2021) Evaluation of rumen protected rapeseed expeller (NovaPro) as an alternative to soya bean meal in dairy cow diets. Animal Feed Science and Technology

106 Novak et al. (ND) Monogastric nutrition. Encyclopedia of Life Support Systems (EOLSS) Available at: www.eolss.net (Accessed 4 October 2021)

107 Wasley, A. (2017) UK has nearly 800 livestock mega farms, investigation reveals. The Guardian. 17 July. Available at: https://www.theguardian.com/environment/2017/jul/17/uk-has-nearly-800-livestock-mega-farms-investigation-reveals (Accessed 4 October 2021)

108 Bureau of Investigative Journalism (2017) Intensive farming in the UK, by numbers. Available at: https://www.thebureauinvestigates.com/stories/2017-07-17/intensive-numbers-of-intensive-farming (Accessed 4 October 2021)

109 WWF (2021) No Food Left Behind Part IV: Benefits & Trade-offs of Food Waste-to-Feed Pathways. Available at: https://www.worldwildlife.org/publications/benefits-trade-offs-of-food-waste-to-feed-pathways

110 WWF-UK and Tesco (2021) Development of a roadmap to scale up insect protein production in the UK for use in animal feed. Adas. Available at: https://www.wwf.org.uk/sites/default/files/2021-06/the_future_of_feed_technical_report.pdf

111 Refresh (2020) Surplus food as animal feed. Available at: https://eu-refresh.org/sites/default/files/06_Karen%20Luyckx%2C%20Jennifer%20David%2C%20Tomoyuki%20Kawashima_animal%20feed.pdf

112 Ibid. NB the feed contained 6% soy but no cereals.

113 van Hal, O. (2019) 'Upcycling food leftovers and grass resources through livestock: Impact of livestock system and productivity', Journal of Cleaner Production, DOI:https://doi.org/10.1016/j.jclepro.2019.01.329

114 Van Selm, B. et al. (2021) 'The compatibility of animal-sourced food and circularity in healthy European diets' DOI:10.21203/rs.3.rs-147410/v1

115 Van Kernebeek, H. R. J. et al. (2016) 'Saving land to feed a growing population: consequences for consumption of crop and livestock products', Int J Life Cycle Assess, 21, pp.677–687, DOI:https://doi.org/10.1007/s11367-015-0923-6

116 Smil, V. (2014) 'Eating meat: Constants and changes', Global Food Security, DOI:https://doi.org/10.1016/j.gfs.2014.06.001

117 van Hal, O. (2019) 'Upcycling food leftovers and grass resources through livestock: Impact of livestock system and productivity', Journal of Cleaner Production, DOI:https://doi.org/10.1016/j.jclepro.2019.01.329

118 Elferink, E. V. et al. (2008) 'Feeding livestock food residue and the consequences for the environmental impact of meat', Journal of Cleaner Production, DOI:http://dx.doi.org/10.1016/j.jclepro.2007.06.008; Van Zanten, H. H. E. et al. (2016) 'Opinion paper: The role of livestock in a sustainable diet: a land-use perspective', Cambridge University Press, DOI:https://doi.org/10.1017/S1751731115002694

119 Schader, C. et al. (2015) 'Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability', Journal of the Royal Society Interface, DOI:https://doi.org/10.1098/rsif.2015.0891

120 Röös, E., et al. (2016) 'Limiting livestock production to pasture and by-products in a search for sustainable diets', Food Policy, 58, pp.1-13, DOI: https://doi.org/10.1016/j.foodpol.2015.10.008

121 Röös, E. et al. (2017) 'Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures', Global Environmental Change, 47 pp.1-12. DOI: https://doi.org/10.1016/j.gloenvcha.2017.09.001

122 Elferink, E. V. et al. (2008) 'Feeding livestock food residue and the consequences for the environmental impact of meat', Journal of Cleaner Production, DOI:http://dx.doi.org/10.1016/j.jclepro.2007.06.008

123 Based on the average protein content of the EAT-Lancet Commission's recommended 400g of animal source foods per person per day (including 250g of milk); Willet, W. et al. (2019) 'Food in The Anthropocene: the EAT-Lancet Commission on Healthy Diets From Sustainable Food Systems', EAT-Lancet Commission, DOI:https://doi.org/10.1016/S0140-6736(18)31788-4; Average protein content is from US Department of Agriculture (USDA) 'Food Data Central'. Available at: https://fdc.nal.usda.gov/ (Accessed 4 October 2021).

124 NHS (2020) Reference intakes explained. Available at: https://www.nhs.uk/live-well/eat-well/what-are-reference-intakes-on-food-labels/

125 British Nutrition Foundation https://www.nutrition.org.uk/nutritionscience/nutrients-food-and-ingredients/protein.html?start=2 (accessed August 2021)

126 British Nutrition Foundation using data from the UK National Diet and Nutrition Survey (NDNS). Available at: https://www.nutrition.org.uk/nutritionscience/nutrients-food-and-ingredients/protein.html?start=2 (Accessed August 2021); Values in grams are calculated based on average protein intake of 76g per person per day

127 Van Selm, B. et al. (2021) 'The compatibility of animal-sourced food and circularity in healthy European diets' DOI:10.21203/rs.3.rs-147410/v1

128 van Hal, O. (2019) 'Upcycling food leftovers and grass resources through livestock: Impact of livestock system and productivity', Journal of Cleaner Production, DOI:https://doi.org/10.1016/j.jclepro.2019.01.329

129 Röös, E. et al. (2017) 'Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures', Global Environmental Change, 47 pp.1-12. DOI: https://doi.org/10.1016/j.gloenvcha.2017.09.001; Schader, C. et al. (2015) 'Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability', Journal of the Royal Society Interface, DOI:https://doi.org/10.1098/rsif.2015.0891

130 Calculation assumes: 1) entire UK population consumes adult diet; 2) fava bean yield of 3.5 tonnes / ha. The increase of 7.5g plant-based protein would leave only 12.5g to be provided from animal sources

131 UK Natural History Museum Biodiversity Intactness Index

132 Soy use in animal feed estimate based on 2017-18 figures. Assumes meal is 0.81 of whole bean by weight. Assumes average yield of 3.5 tonnes soybean per hectare.

133 WWF-UK (2017) 'Eating for 2 Degrees: New and updated Livewell Plates'

134 Poore, J., & Nemecek, T. (2018). 'Reducing food's environmental impacts through producers and consumers'. Science, 360(6392), pp.987-992. DOI:10.1126/science.aaq0216

135 AHDB (2021) 'GB Animal Feed Production'. Available at: https://ahdb.org.uk/cereals-oilseeds/cereal-use-in-gb-animal-feed-production (Accessed 4 October 2021)

136 DAERA (2021) 'Animal Feed Statistics - 2020' Available at: https://www.daera-ni.gov.uk/publications/animal-feed-statistics-2009-2020 (Accessed 4 October 2021)

137 Hill, O. (2016) '30% of total English maize crop goes for anaerobic digestion', Farmers Weekly. Available at: https://www.fwi.co.uk/arable/other-crops/30-percent-of-total-english-maize-crop-goes-for-anaerobic-digestion (Accessed 4 October 2021)

138 AHDB (2021) ;UK cereals supply and demand estimates'. Available at: https://ahdb.org.uk/cereals-oilseeds/uk-cereals-supply-demand-balance-sheets (Accessed 4 October 2021)

139 AHDB (2021) 'UK imports of non-cereal feed ingredients (NCFIs)'. Available at: https://ahdb.org.uk/cereals-oilseeds/trade-data (Accessed 4 October 2021)

140 Efeca (2019) UK Roundtable on Sustainable Soya: Annual progress report, 2019. Available at: https://www.efeca.com/wp-content/uploads/2019/12/UK-RT-on-Sustainable-Soya-APR-2019-final.pdf

141 AHDB (2021) 'UK imports of non-cereal feed ingredients (NCFIs)'. Available at: https://ahdb.org.uk/cereals-oilseeds/trade-data (Accessed 4 October 2021)

FIGURES

Figure 1 Low opportunity cost livestock feed as part of a circular economy 8
Figure 2 Global livestock feed ration composition 22
Figure 3 Food waste hierarchy 24
Figure 4 Domestic supply, imports and exports of animal produce, 2019 30
Figure 5 UK utilised agricultural land use showing area of cropland and different categories of grassland 31
Figure 6 Non-grass feed in the UK, 2019, by tonnage. 34
Figure 7 Inputs to UK livestock feed (2019) 35
Figure 8 A breakdown of 31m tonnes of feed consumed in the UK in 2019 36
Figure 9 The uses of soybean meal over the period 1964 - 2019, globally 42
Figure 10 Summary of opportunity cost of feed inputs to UK livestock 48
Figure 11 Diet composition for adult sheep reared for meat 50
Figure 12 Diet composition for adult cattle (meat and dairy) 50
Figure 13 Diet composition for pigs (industrial and intermediate systems) 52
Figure 14 Diet composition for poultry (broilers and layers) 52
Figure 15 Sources of protein in the diet of UK adults 56

TABLES

Table 1 Key issues in defining low opportunity cost feedstuffs 23
Table 2 Summary of inputs to UK livestock nutrition 29
Table 3 Area of key UK crops used for animal feed, 2019 37
Table 4 Crop-based inputs to UK livestock feed 39
Table 5 By-product inputs to UK livestock feed 41
Table 6 Soy cake and meal in UK livestock feed 43
Table 7 Other inputs to UK livestock feed 43
Table 8 Volumes of substrate potentially available for animal feed from currently permitted substrate streams and from most viable additional substrate streams 46
Table 9 Summary of opportunity cost status of feed inputs, and colour codes used in this document. 49
Table 10 Key assumptions of LOC feed system models 55
Table 11 Current and recommended protein in diets, per person per day 57

For a future where people and nature thrive | wwf.org.uk