



# Assessment of the land use implications of innovation in agricultural production

LUNZ Hub Agile Policy Centre

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## Report For

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# Executive Summary

## Approach

Defra commissioned this research to better understand how innovations in production methods could impact land use over the longer term. Land use change is a key consideration for environmental policy and a better understanding of how environmental and innovation drivers might interact was desired.

This project built on Defra's earlier commissioned foresight study by Vivid Economics, which aimed to improve understanding of agri-food innovation developments. It focused on seven innovation areas (with innovation referring broadly to changes to existing practices, operationally and behaviourally as well as technologically) and considered their likely impact on a range of environmental indicators, of which one was land use. This current research utilises a similar approach of grouping agri-food innovations into broad themes, and the choice of themes is heavily based on the earlier study, but the current review has a narrower focus on the innovations' impacts on land use, and specifically how these impacts could occur in the UK context.

The agri-food innovations in scope of this research (which are slightly different to the earlier work) are:

- Protein transition
- Vertical agriculture
- Increased productivity of farming
- Genetic technologies
- Circular economy
- Regenerative agriculture

This research commenced with a review of the previous study and a scoping exercise with Defra to ensure that the research prioritised themes of interest. This was followed by a review of relevant literature on the agri-innovations to determine their potential magnitude of change upon land use in the UK (including quantification where possible), potential speed and likely uptake. The assessment also included a category on confidence in potential for impact, given the uncertainty of these projections.

## Key findings

The most significant findings are that though most of these agricultural innovations have the **potential** to lead to some reduction in agricultural land use, none are expected to occur at a scale that would be truly transformative. This is both because of **technical limitations** of the innovations themselves – the feasible extent of technological development represents significant uncertainty, especially on the 20- to 25-year timescale of this study – and because there are significant social and economic barriers that could limit on-the-ground uptake of the innovations. Our assessment is that **social and especially economic constraints** on how these innovations can be rolled out in an economically feasible way at scale are likely to constrain and slow adoption for many, even if technological readiness is achieved.

Most innovations are expected to be technologically available and adopted to some extent by 2040, with some potential resulting implications for land use, but the **magnitude of change is highly uncertain**, with limited quantification possible. The quantification of the scale of change is frequently dependent on **limited sources**, and expert review of this report suggests these may tend to be over-optimistic, as they primarily draw from academic studies and small-scale trials without necessarily adequately accounting for the challenges and realities of large-scale implementation.

One of the key findings of the research was to highlight that the **causal link** between these innovations and agricultural land use change is **not equally strong** for all innovations. Some innovations may focus heavily on benefits other than increased yield productivity, limiting the scope for land use efficiencies. Additionally, even where yield or productivity gains are made, this may not result in land use actually changing – it may simply see the same area of land used more intensively. Each agri-innovation was determined to lead to some environmental benefits in the earlier study. However, this study's focus on land use specifically highlighted that this is not always the most studied impact for these innovations, with the literature often focused on the benefits in relation to greenhouse gas emissions rather than land use.

It is also important to note that the UK's food system is closely connected with the **wider global food system** and global food markets, and therefore when considering the potential impacts of agricultural innovations on land use in the UK, it may be that changes result in overseas. These may be **more significant** than in the UK itself (for example, from a decrease in imported soy feeds). This study focuses on identifying UK impact but provides comments where there is scope for the UK's land footprint overseas to be impacted.

Table E-1 provides the range of quantified potential impacts on land use from the implementation of each innovation alongside the assessment of the speed and uptake of each innovation, and an **indication of confidence**. As stated above, all land use change should be considered as **potential** due to the technical and socio-economic barriers described above, and the **uncertainty** relating to the causal link between increased productivity and reduced land use. The quantified land use change figures represent a potential trajectory that considers the feasible technical development but simultaneously incorporates the impact of the above barriers on likely change. As stated above, quantification is limited as most estimates are based on academic studies and small-scale trials without adequately accounting for the challenges and realities of large-scale implementation. For some of these innovations there is a cap on the potential maximum change.

**Table E-1: Summary of the potential magnitude (and quantified range) and speed of land use change due to uptake of agricultural innovations and confidence in this assessment**

Theme	Magnitude	Range in estimates of potential land use change	Speed	Likely uptake	Confidence in potential for impact
<b>Protein transition</b>	Significant	Highly Uncertain*	Gradual	Moderately	Low
<b>Vertical agriculture</b>	Minor	Less than 70,000 hectares	Intermediate	Moderately	Medium
<b>Precision agriculture technologies</b>	Minor	Between 170,000-339,000 hectares	Rapid	Likely	Medium
<b>Genetic technologies</b>	Significant	Between 214,000-1.28 million hectares (arable only)	Intermediate	Likely	Medium
<b>Circular economy</b>	Minor	Between 480,000 and 600,000 hectares	Gradual	Likely	Medium
<b>Regenerative agriculture</b>	Insignificant / negative	Between -700,000 to -1.1 million hectares (arable only)	Intermediate	Unlikely – Moderately Likely**	Low

\*This figure carries particularly strong uncertainty as – unlike the other innovations – the extent of change is highly dependent on demand-side factors around consumption preferences and behaviour change which are challenging to predict, though current consumption trends, and the scope for changes in animal feed, mean some change is likely.

\*\*We depart from the single classification in this case, because our assessment is that the bundle of practices grouped under the term 'regenerative agriculture' may see very differential take-up.

Given the interdependencies of the agri-innovations and uncertainties (as described above), this report does not identify which specific agri-innovation might have the most significant impact on agricultural land use, though it does give a qualitative estimate of potential for each. The diverse ways in which these interactions may reinforce or constrain the collective impact on land use are explored in Section 3.8. It is likely that a diverse portfolio of agri-innovations will collectively deliver change – and that socio-economic viability will be as, if not more, important than technological developments to the mix that is actually achieved.

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# 1.0 Introduction

Eunomia is pleased to present this report on the “Assessment of the land use implications of agricultural production innovation and change” for the Department for Environment, Food and Rural Affairs (Defra).

## 1.1 Background to the project

Defra commissioned this work to better understand how innovations in production methods could impact land use over the longer term. Land use change is a key consideration for environmental policy and a better understanding of how environmental and innovation drivers might interact was desired.

This project built on Defra's earlier commissioned foresight study by Vivid Economics.<sup>1</sup> Their foresight study to inform agri-food innovation development and realisation was undertaken in 2021-22 with the objective of improving understanding of the agri-food innovation landscape. It focused on seven innovation areas and considered their likely impact on a range of environmental indicators, of which one was land use. This research utilises a similar approach of grouping agri-food innovations into broad themes, which are based on the earlier study, but has a narrower focus on their impacts on land use only, and specifically how these impacts could occur in the UK context, in contrast to the global scope of the earlier work.

It is important to note that **‘innovation’ in the context of this study broadly refers to changes from existing practices**. This may be in the form of implementation of a technological innovation (such as the use of genetic technologies to increase resistance to diseases) but equally may refer to operational changes or a social or behavioural innovation (such as the decision to rotate and combine crops and livestock as part of regenerative agriculture practices). The agri-food innovation themes in scope of this research are below. These are based on the Vivid Economics report for consistency, though some rationalisation and refocusing has been applied to maximise relevance to the land use focus. This gave six innovation categories:

- **Protein transition** (both relating to potential changes to human protein sources and to potential changes in animal feed protein sources, a distinction that was not a focus of the earlier work);
- **Vertical agriculture** (considering controlled environmental indoor production in general but focusing on vertical agriculture specifically);
- **Increased productivity of farming** (combining two themes from the earlier study: increased efficiency of inputs and implementation of precision agriculture techniques);
- **Genetic technologies** (including gene editing, gene drives, genetic modification and selective breeding);
- **Circular economy** (focusing on on-farm, pre-farm gate food losses as opposed to food loss and waste occurring downstream such as consumer food waste, which is a narrower framing than in the earlier study, but reflective of where this study identified the greatest land use impacts)
- **Regenerative agriculture** (recognising that there are no standardised set of processes or a standard definition of regenerative agriculture, therefore this theme covers viable innovations that may impact land use).

In assessing the potential impacts of innovation on land use in the UK, it is also important to note that the UK food system is intrinsically interconnected with the wider global food system and that land use change in many cases is a global context, hence any consideration of changing land use through innovation in the UK should also consider wider international context. This study focuses on identifying UK impact but provides comments where there is scope for the UK's land footprint overseas to be impacted.

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<sup>1</sup> Vivid Economics, 2022. *Foresight Study to inform Agri-Food Innovation Development and Realisation*. Unpublished.

## 1.2 Objective of the project

The objective of the project is to:

*Research, analyse and quantify (where possible) how the agri-food production innovations identified may impact land-use in the UK over the medium to long-term (defined as 2035-2050).*

## 1.3 Structure of the report

This concise summary report is structured as follows:

- The methodology followed is briefly outlined in **Section 2.0**, including:
  - a description of the categories used to present our results in **Section 2.1**,
  - an overview of the current agricultural land use data used to contextualise the results in **Section 2.2**.
- The results of the research are presented in **Section 3.0**, including:
  - a discussion of the overarching impact across all or multiple innovations and any assumptions made during the research in **Section 3.1**,
  - the results for each innovation are presented in **Section 3.2** to **Section 3.7**. For each theme, the following is provided:
    - an overview of what the innovation consists of;
    - its likely impact across land used for livestock, horticulture and arable crops;
    - potential feasible magnitude (including quantification where possible);
    - barriers that might prevent this magnitude of change from being realised;
    - potential speed of change;
    - the likely uptake of the innovation (considering the barriers);
    - our confidence in the predicted impact being realised; and
    - a discussion on the potential for unintended consequences.
  - the potential interactions between and collective impact of the innovations are discussed in **Section 3.8**.
- The conclusions of the research are presented in **Section 4.0**.
- References for evidence for this research are listed in **Appendix A.1.0**.

## 2.0 Methodology

A high-level overview of the methodology is as follows.

- **Inception and scope refinement.** In recognition of the limited scope and time available for this research, the inception phase was used to identify priority areas of research.
- **Review previous agri-innovation foresight study.** The seven themes of the previous study by Vivid Economics were analysed for relevance for inclusion in this research, given the more precise focus, and time elapsed since the earlier study.
- **Qualitative assessment.** A qualitative assessment literature review framework was created to enable rapid review of relevant literature, using the following headers and prompts. Suitable literature was determined according to relevance, source reliability and recency using platforms such as Science Direct and Google Scholar. Where evidence came from overseas studies, applicability to the UK context was assessed. This structure enabled us to identify what the 'maximum realistic change' could be once all technological and social feasibility and barriers were considered.
  - What does this innovation mean / look like? Will it be systemic or incremental?
  - What is the direction and magnitude of displacement without barriers?
  - What is the current Technology Readiness Level of this innovation?
  - How fast [at the decadal level] would this innovation occur?
  - What are the barriers to uptake? How significant are the barriers?
  - How might the barriers be overcome?
  - Can the impacts be quantified? What is the best-case scenario?
  - What is the potential for unintended consequences? [particularly land use overseas]
- **Develop trajectories and impact assessment.** Once the research was complete, this next step in the process involved determining the most suitable categories for categorising the impact of each innovation upon the axes of magnitude, speed, uptake and certainty. However, in practice, evidence on quantification was limited and typically came from small-scale trials or general extrapolation. These estimates should be taken as indicative rather than projections.
- **Reporting.** The findings were presented in this concise summary report.

This was a rapid project with limited budget and therefore the literature review was selective and focused heavily on evidence of technical potential. This focus was mitigated by discussion of the preliminary results with internal experts at Eonomia, and an external reviewer, James Clarke, at ADAS. The results and discussion are presented at a high level and are intended to be used to inform thinking about where innovation may offer most potential, rather than be a definitive statement on what might happen. This is especially true given that change for all innovations will be heavily dependent on social and economic factors in addition to technical ones.

## 2.1 Categorisation of results

The categories used to define the potential future impact of each innovation on agricultural land use in the UK are presented in Table 2-1 (overleaf). The categories are defined as follows:

- **Potential magnitude:** this scale of change that the innovation is expected to have on land use, by identifying an optimistic (i.e., favourable conditions) but realistic (i.e., no radical contextual shifts beyond the innovation itself) potential for change;
- **Potential speed:** the anticipated rate of change (in terms of approximate decades to 2050) that the implementation of the innovation may cause;
- **Likely uptake:** the probable rate of adoption of the innovation by stakeholders in the real world;

- **Confidence in potential for impact:** a qualitative assessment of the level of uncertainty.

There is significant uncertainty across multiple dimensions of each innovation. These scorings are therefore most useful in comparing innovations, rather than in assessing the likely absolute impact of innovation on land use, especially given the confounding factors and dependencies for both land use change generally, and in relation to social and economic viability in practice.

Based on the literature and expert review, the expectation of **likely uptake** is towards the lower end of the feasibility range given the contextual barriers for every innovation. Additional efforts (primarily policy-related as opposed to technological) would be needed to enable change at greater scales, even when each technology or each innovation achieves its potential.

**Table 2-1: Axes of impact**

Potential magnitude	Potential speed	Likely uptake	Confidence in potential for impact
Insignificant / negative			
Minor	Gradual	Unlikely	Low
Significant	Intermediate	Moderately likely	Medium
Transformative	Rapid	Likely	High

## 2.2 Agricultural land use in the UK

Where possible based on available evidence and data, the quantified impact for each innovation is provided in Section 3.0, though these estimates are highly caveated. The data on agricultural land use in the UK used for these estimates is provided in Table 2-2. The primary interest of this research is in implications for UK production and land use, but any potential impacts of demand displacement overseas are considered for each theme.

**Table 2-2: Agricultural land use in the UK<sup>2</sup>**

Land use	Hectares
Permanent grassland	9,379,643
Arable crops	4,133,687
Other land on agricultural holdings	1,301,358
Temporary grass under 5 years old	1,275,482
Common rough grazing	1,197,329
Uncropped arable land	616,054

<sup>2</sup> Defra, 2024. *Agricultural land use in the United Kingdom*. Available at: <https://www.gov.uk/government/statistics/agricultural-land-use-in-the-united-kingdom>

Land use	Hectares
Horticultural crops	142,244
<b>Total agricultural land</b>	<b>18,045,797</b>

There are some general points to note on this categorisation of land use:

- The potential impacts on land use in the rest of this study are based on a threefold split: livestock, arable and horticulture. This reflects a convenient shorthand to triage the evidence on innovations but these categories do not map precisely onto the above land use categories. However, broadly speaking, permanent grassland, temporary grasslands and common rough grazing are used for livestock whereas arable crops and uncropped arable land, and horticultural land are arable and horticultural lands respectively. Other land on agricultural holdings is not typically used for these uses.
- Within livestock it is also important to note that cattle and sheep rearing use significantly more land than poultry for meat or eggs, and that some arable lands are used to produce crops for animal feed. Feed is also frequently imported (primarily soy) which complicates consideration of likely impacts in the UK.
- Agricultural land is not directly correlated with land used for food (e.g., land used to grow crops for biofuels), though for the purposes of this project, the land use listed in Table 2-2 is considered to be land that could change as a result of these innovations.

## 3.0 Results

This section presents the results of the analysis for each innovation, starting with key themes that emerged from researching multiple innovations and from a holistic analysis of the potential collective impact of the innovations.

### 3.1 Key considerations

There are numerous points that emerged from the literature review that relate to the overarching impact on agricultural land use change across all or multiple innovations or assumptions that had to be made. These include:

- **The food system is global and interconnected.** The UK's food landscape is inherently interconnected with imports and exports from multiple countries and bioregions and therefore changes explored in this report (e.g., protein transition of animal feed) may have more significant impacts abroad than on agricultural land use in the UK.<sup>3</sup> In general, changes in consumption of products in the UK does not necessarily equate to corresponding changes in UK production of those products, and consequently on the associated land footprint.
- **Land use change is not the driving force behind the implementation of these agri-innovations.** Land use change occurs as a byproduct of these innovations, which will typically be adopted based on their perceived economic benefit, or due to compliance with regulatory requirements. Even where environmental factors are influencing take-up this is more likely to be linked to carbon, biodiversity, or resilience, rather than land use change directly.
- **A change in land use change as a result of increased input efficiency is not inevitable.**
  - The largest impact of many of the innovations is on increased efficiency of inputs (e.g., requiring less nitrate fertiliser to produce the same crop volumes). Though this has environmental benefits (e.g., less water pollution from nitrates, fewer nitrous oxide emissions), reduced agricultural land use may not be a / the most significant environmental outcome.
  - Additionally, socioeconomic benefits from increased input efficiency (e.g. increased financial resilience of farms due to less dependence on volatile input prices) can be realised independent of land use changes.
  - Moreover, the UK food system, like others globally, faces increasing vulnerability to climate change-related shocks, particularly extreme weather events. While some innovations discussed in this report may enhance resilience and productivity, they may primarily serve to maintain rather than increase yields in an increasingly challenging environment.
  - The implementation or uptake of these innovations may lead to efficiencies which cause a fall in production costs per unit output. At an individual farm-level, this does not necessarily equate to a reduction in land use; instead, this could lead to a rebound effect of increased production or more intense land use.
- **Demand is assumed to remain constant.** The complexity of the UK food system and its interactions with multitudinous relevant factors meant that various assumptions were made to enable the individual consideration of each innovation. Throughout this research it was assumed that

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<sup>3</sup> Lumsden et al., 2024. *Critical overview of the implications of a global protein transition in the face of climate change: Key unknowns and research imperatives*. Available at: <https://www.sciencedirect.com/science/article/pii/S2590332224003178>

demand for food products remains constant in the UK, not accounting for population change or changing preferences except where directly relevant (e.g., for protein transition).

- **Not all land is created equal.** The quality of the agricultural land that might be 'freed up' from these innovations needs to be considered, as land differs vastly both in terms of agricultural productivity (suitability and flexibility) and in terms of potential environmental benefits (e.g., biodiversity gain) that it could provide. This also relates to the UK's overseas footprint (positively or negatively) if international substitution effects were to occur. There are also innovations or expected changes that could occur that are not considered in this report, for example, the innovation of cultivating novel crops on peatlands that enable production with raised water tables and reduce emissions.
- **Land use is one of many environmental metrics.** Much of the literature focuses on the potential greenhouse gas emission reductions that could be achieved from these innovations. Agricultural land use reduction and emissions reductions are not directly correlated and therefore land use must be considered alongside other environmental priorities. Similarly, land use in other locations may have a greater emissions impact, and the comparable benefit of these options needs to be better understood. Finally, reducing agricultural land use can conflict with the need to reduce greenhouse gas emissions and protect biodiversity. The intensification of agriculture (producing more on a smaller area), which is beneficial for land use, may be associated with different environmental concerns, such as from fertiliser use or to biodiversity etc.<sup>4</sup>
- **Non-technical barriers need to be overcome as well.** It is not always clear how barriers including behavioural, cultural and structural barriers (such as market dynamics and structures causing overproduction as a form of mitigation, leading to on-farm food loss) can be overcome, which creates some uncertainty in how much change should be considered realistic. Therefore, **all land use change mentioned throughout this report should be considered as potential.** Examples of non-technical barriers include:
  - **Profitability is the driving factor for implementation, which currently is a barrier.** Many of the innovations listed here are already available to farmers to some degree from a technological perspective but have not been implemented due to financial (and cultural) reasons. Uptake would depend heavily on the financial health of the sector, capital availability, willingness to invest for longer term gains and economic benefit of the new technology, and this is considered a significant and recurring barrier for innovations that require upfront investment or may not increase yields immediately.<sup>5</sup>
  - **Behavioural change and cultural shifts are critical.** The implementation of these innovations requires some behavioural change or cultural shift both from farmers and other stakeholders (including consumers); many barriers are therefore behavioural as opposed to technical.
  - **Regulation and policy will be key determinants of change.** It is out of scope for this project to highlight specific policies that might help or hinder innovation, but the regulatory and policy landscape will be a critical determinant of the speed and scale of take up for multiple technologies. Regulation may limit the potential impact of these innovations (intentionally or otherwise). In order for innovations to be implemented, stakeholders need assurance that future policy will provide similar incentives, especially as many innovations (e.g., genetic technologies) are implemented over long timescales (over which several governments and ministers may preside and bring different priorities).

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<sup>4</sup> Simon et al., 2024. *Circular food system approaches can support current European protein intake levels while reducing land use and greenhouse gas emissions.* Available at: <https://www.nature.com/articles/s43016-024-00975-2#:~:text=Abstract,enhance%20human%20and%20planetary%20health>.

<sup>5</sup> Campbell, D. and Munden-Dixon, K. 2018. *On-farm food loss: farmer perspectives on food waste.* Available at: <https://open.clemson.edu/joe/vol56/iss3/23/>

- **Potential conflicts between innovations.** The interactions between the innovations and how they may complement each other to reduce agricultural land use is documented in Section 3.8. However there is also potential for conflict – for example, increasing demand for food waste to use as a feedstock (e.g., for insect cultivation for animal feed) may remove incentives to implement circular economy principles and reduce on-farm pre-farm food waste.
- **Data is limited and likely to be optimistic.** The literature that is willing to quantify potential changes may be optimistic and/or be based on limited trials that show large potential when scaled in theory but are likely to be much more modest in real-world scenarios. This is considered for each of the following sections.

This research was of necessity a very rapid review and focused on literature exploring the potential of the specific interventions. Our assessment is that social and especially economic constraints on how these innovations can be rolled out in an economically feasible way at scale is a more likely and significant constraint than technological readiness. There may also be some system complexities (e.g. 'bite back' impacts such as pests adapting to changes) that reduce both environmental benefits and economic viability. For this reason, we believe the literature reviewed in this study, and the estimates that can be achieved extrapolating from this evidence to the overall market, is likely to over-estimate the scale of change that is likely to ultimately be achieved. There is arguably a need for closer interaction between those pursuing more technical research, and those with practical applied knowledge of what would be required to adopt these innovations in real world operations. For innovations that are not ready for implementation at the field-level, this lack of a quantified evidence base on the potential impacts is challenging for decision-making for farmers and producers (and policy makers).

## 3.2 Innovation Area 1: Protein transition

### 3.2.1 Overview of scope

For the purposes of this report, protein transition as an agri-food innovation refers to:

- **a reduction in production of livestock protein for consumption in human diets**, replaced by alternative proteins such as tofu, beans, mycoproteins and cultured meats; and
- **a reduction in production of crops for consumption as animal feed**, replaced by various plant-based and animal-based sources such as black soldier fly larvae.

**Scope restrictions:** The potential for consumer preferences to shift within meat consumption (e.g., from beef to chicken or fish) is not considered as it is not an innovation and is a demand-side rather than production-side change, with the latter being the focus of this study. It was initially agreed to consider separately the impact of a protein transition away from red meat and the potential for a protein transition away from other meats and dairy sources. However, the lack of available data means that these were not able to be analysed or considered separately. The assessment here focuses on supply-side drivers that may lead to change, rather than demand-side factors, though demand (or the lack of it) will be a key point influencing the speed and scale of uptake, and is a significant source of uncertainty in quantifying the potential for change.

**Technology readiness and adaption to date:** The range of proteins that could contribute to the protein transition have differing levels of technological readiness and maturity. For human consumption, most alternative proteins are available on the market somewhere in the world, if not widespread, or necessarily available in the UK. Some plant-based substitutes are well established, while others, such as cultured meats, are at a much earlier stage and are not yet mass-market products. For animal feed, some proteins (such as feed produced from microbes) has been well-established in the industry for decades, whilst others have been recently legally enabled for use (such as the use of insect feed in

poultry and pigs in the EU), others (such as mycoprotein fish feed)<sup>6</sup> are being scaled up whilst others including insects, micro algae, seaweed and duckweed are less well established and still in development.

## 3.2.2 Potential impact

### 3.2.2.1 How could the innovation potentially affect land use?

This innovation has the potential to cause **significant change** in agricultural production practices and land use. This reflects both the potential of the technology, and the large amount of land used for livestock (either directly, or for feed). The increased availability of plant-based and non-meat alternatives for human consumption could lead to the systemic displacement of meat in diets by new products, leading to a reduction in agricultural land used both for rearing livestock and producing animal feed.<sup>7</sup> Likewise, the increased availability of innovative animal feeds could lead to a displacement of traditional feedstocks, leading to a reduction in land use required for animal feed production.<sup>8</sup> The summarised impact of change in terms of magnitude, likelihood and speed is presented in Table 3-1. The current market share of alternative proteins is only 1% for meat alternatives as a proportion of the meat market, and 3% for dairy alternatives<sup>9</sup>; there is little data on the current market share of alternative animal feedstocks. It should also be noted that the significance of imported soy feed is a constraint on the impact of this innovation on UK land use.<sup>10</sup>

**Table 3-1: Expected impact of change from protein transition innovations**

Impact	Magnitude	Speed	Likely uptake	Confidence in potential for impact
Scale	Significant	Gradual	Moderately likely	Low*

\*Uncertainty is high as changes due to consumption shifts are highly dependent on demand side factors that were not a focus of this study.

### 3.2.2.2 Potential magnitude

**Potential for change:** The evidence indicates that the magnitude of change in land use as a result of the protein transition is expected to be **significant** (though not transformative). This innovation is expected to manifest in a systemic shift towards sources of protein with a significantly smaller land use footprint, driven by market forces, consumer preferences and needs, and policy initiatives responding to growing global protein demand and the environmental limitations of current agricultural practices. If, theoretically, alternative sources of protein were to become 'the norm', then global land use (both for livestock rearing and for animal feed production) could be reduced by over 90% according to one source<sup>11</sup> - this is however a theoretical maximum that is extremely unlikely to occur due to the barriers discussed in

<sup>6</sup> Enifer, 2024. *Enifer takes giant step closer to scaling up aquafeed mycoprotein production*. Available at: <https://www.fishfarmingexpert.com/enifer-skretting/enifer-takes-giant-step-closer-to-scaling-up-aquafeed-mycoprotein-production/1610979>

<sup>7</sup> Green Alliance, 2024. *A new land dividend: the opportunity of alternative proteins in Europe*. Available at: <https://green-alliance.org.uk/publication/a-new-land-dividend-the-opportunity-of-alternative-proteins-in-europe/>

<sup>8</sup> WWF, 2022. *The Future of Feed*. Available at: <https://www.wwf.org.uk/learn/low-opportunity-cost-feed>

<sup>9</sup> UKRI, 2022. *Alternative proteins: identifying UK priorities*. Available at: <https://www.ukri.org/wp-content/uploads/2022/06/IUK-100622-AlternativeProteinsReport-FINAL.pdf>

<sup>10</sup> EU Science Hub, 2024. *Can the EU chart a sustainable transition to greater protein self-sufficiency?* Available at: [https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/can-eu-chart-sustainable-transition-greater-protein-self-sufficiency-2024-10-08\\_en](https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/can-eu-chart-sustainable-transition-greater-protein-self-sufficiency-2024-10-08_en)

<sup>11</sup> Pexas et al., 2023. *The future of protein sources in livestock feeds: implications for sustainability and food safety*. Available at: <https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2023.1188467/full>

Section 3.2.2.3. Likewise, mycoproteins, algae and insects could theoretically replace the need for any arable land to produce animal feed but are practically unlikely to lead to this scale of change.

**Evidence availability:** There is some evidence available (both quantitatively and qualitatively) on the potential impacts of a protein transition of land use, but there is huge uncertainty as to the scale of change that might occur and therefore the range of potential outcomes on land use is large. This topic can also be viewed as politically contentious and much of the quantitative data was sourced from grey literature as opposed to academic sources.

**Scope for quantification:** One source suggests that in a 'low intervention' scenario of alternative proteins replacing meat and dairy for human consumption, approximately 4 million hectares of domestic farmland in the UK could be 'freed' (~ a 20% reduction from current levels), and that under a 'high intervention' scenario, this could increase to 10 million hectares of domestic farmland freed or a 57% reduction (along with another 10 million hectares of farmland abroad).<sup>12</sup> However, it is important to note that this figure arises from research conducted by organisations that are pushing for this protein transition to occur. This quantification broadly aligns with academic literature which suggests that under scenarios keeping the consumption of protein within recommended protein intake guidelines, agricultural land use could be reduced by between 30 and 50% (though this is across Europe rather than specific to the UK).<sup>13</sup> When applied to the UK's current agricultural land use, this would equate to between **5 and 9 million hectares** of land freed up.

Equally, one source suggests that under an animal feed transition, if cereal crops were excluded from animal feeds, the expected land use change is projected to be approximately 1.9 million hectares.<sup>14</sup> Growing cereal crops for animal feedstocks currently uses around 40% of the UK's arable land area (approximately 2 million hectares) and another 850,000 hectares abroad. The projected impact varies depending on the protein or alternative feedstock that is utilised: insect farming could potentially reduce land use by 95%, whereas protein extraction from yeast is associated with 71% less land use compared to soy or other oilseed crops. It is unlikely (given the barriers listed below) that an 100% displacement of cereal crops would occur, so instead a 50% displacement rate is utilised (based on our assessment of the impact and significance of the barriers) to give an overall displacement of approximately an additional **one million hectares** of land use 'freed up'.

### 3.2.2.3 Barriers

The numbers above might imply a transformative change, however, there are multiple barriers that could prevent the protein transition from occurring either in human diets or animal feed, and from the implementation of this innovation leading to the potential maximum change in agricultural land use. These include:

- **Price barriers.**
  - Human consumption: changes to production in this space will be dependent on matching changes in consumer preferences.<sup>15</sup> One key element in this may be price. Multiple factors will determine the price of both animal based and alternative proteins. innovative forms of protein are currently available on the market but have not succeeded in displacing traditional proteins at a widespread scale, perhaps due to not providing a

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<sup>12</sup> Green Alliance, 2024. *A new land dividend: the opportunity of alternative proteins in Europe – Technical Report*. Available at: <https://green-alliance.org.uk/publication/a-new-land-dividend-the-opportunity-of-alternative-proteins-in-europe/#:~:text=Under%20a%20high%20innovation%20scenario,nature%20recovery%20and%20carbon%20storage>.

<sup>13</sup> Simon et al., 2024. *Circular food system approaches can support current European protein intake levels while reducing land use and greenhouse gas emissions*. Available at: <https://www.nature.com/articles/s43016-024-00975-2#:~:text=Abstract,enhance%20human%20and%20planetary%20health>.

<sup>14</sup> Pexas et al., 2023. *The future of protein sources in livestock feeds: implications for sustainability and food safety*. Available at: <https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2023.1188467/full>

<sup>15</sup> Dulvins and Baret, 2024. *A systematic review of the definitions, narratives and paths forwards for a protein transition in high-income countries*. Available at: <https://www.nature.com/articles/s43016-023-00906-7>

significant price differential to traditional proteins. Moreover the economics of producing these innovative alternative proteins currently face challenges: while traditional agriculture benefits from various support mechanisms, novel food production methods like mycoprotein require significant up-front investment and technological development, and typically fall outside traditional agricultural support frameworks (such as subsidies in both the UK and the wider international market), which can create an uneven playing field in terms of production costs.<sup>16</sup>

- Animal feed: for animal feed, economies of scale combined with current subsidies and market structures gives traditional animal feed crops a price advantage. However, if product equivalence could be proven, change in this segment could perhaps be faster than for consumers.<sup>17,18</sup>

- **Significant behavioural change required.**

- Human consumption: as above, innovative forms of protein have not become widespread in the market despite being technologically available. The speed of change in consumer preferences would be a key factor in the protein transition for human consumption, and would depend on taste, price, and perceptions of quality and health impact. Cultural factors may also be important.<sup>19</sup>
- Animal feed: similarly, for implementing innovative animal feeds, farmers might need to change established practices and market structures. Nonetheless, as businesses, they may be more likely to respond to purely market drivers, and the extent to which alternative feeds are made available competitively through conventional suppliers is likely to be important.<sup>20,21</sup>

- **Feedstock competition and uncertainties.**

- Animal feed: there are many emerging uses for waste products as a solution to numerous environmental problems, which could lead to conflict over competition for waste products for use as animal feed (e.g., for insects). There are also risks that these models start to rely on purpose-grown inputs (e.g. for insect feed) rather than material that was previously food surplus or waste, or crop residues (purpose grown feedstocks might prove more reliable or consistent for example). This would significantly undermine any positive land use impacts.

- **Regulatory environment.**

- Animal feed: the use of alternative animal feeds is tightly regulated and in some cases restricted (e.g., in the UK, feed safety regulations prohibit the use of black soldier fly larvae for livestock although it is permitted in aquaculture<sup>22</sup>).

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<sup>16</sup> Burton, 2019. *The potential impact of synthetic animal protein on livestock production: The new “war against agriculture”?* Available at: <https://www.sciencedirect.com/science/article/abs/pii/S0743016718309811>

<sup>17</sup> Pexas et al., 2023. *The future of protein sources in livestock feeds: implications for sustainability and food safety*. Available at: <https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2023.1188467/full>

<sup>18</sup> Frontier Economics, 2023. *Delivering insect-based feed at scale*. Available at: [https://www.frontier-economics.com/media/o12xcjt/frontier-economics\\_delivering-insect-feed-at-scale\\_final-report\\_01-12-23.pdf](https://www.frontier-economics.com/media/o12xcjt/frontier-economics_delivering-insect-feed-at-scale_final-report_01-12-23.pdf)

<sup>19</sup> Duluins and Baret, 2024. *A systematic review of the definitions, narratives and paths forwards for a protein transition in high-income countries*. Available at: <https://www.nature.com/articles/s43016-023-00906-7>

<sup>20</sup> Ermgassen et al., 2018. *Support amongst UK pig farmers and agricultural stakeholders for the use of food losses in animal feed*. Available at: <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0196288>

<sup>21</sup> Verbeke et al., 2015. *Insects in animal feed: Acceptance and its determinants among farmers, agriculture sector stakeholders and citizens*. Available at: <https://www.sciencedirect.com/science/article/abs/pii/S0377840115001121>

<sup>22</sup> Frontier Economics, 2023. *Delivering insect-based feed at scale*. Available at: [https://www.frontier-economics.com/media/o12xcjt/frontier-economics\\_delivering-insect-feed-at-scale\\_final-report\\_01-12-23.pdf](https://www.frontier-economics.com/media/o12xcjt/frontier-economics_delivering-insect-feed-at-scale_final-report_01-12-23.pdf)

### 3.2.2.4 Potential speed

Our interpretation of the evidence indicates that this innovation (and consequent projected impact on land use) is likely to occur at a **gradual** rate, mostly because behaviour change on farms and in relation to consumption preferences can often take a long time to embed. This will also be reflected in the rate of any consequential land use change.

Existing alternative proteins for human consumption exist and have gained market share over time. A continued gradual increase from 2025 seems the most credible trajectory at present, supported by an increasing range of products, with increased prevalence in **2030-2040** for cultured meats and mycoproteins, and **2040-2050** for algae and even more innovative products that are yet to be commercialised and brought to market.<sup>23</sup>

In the absence of major barriers, the use of alternative animal feedstocks could scale up significantly by **2040-2050**; the products exist and some have been commercially piloted successfully. However, the behavioural barriers to change could slow this significantly. Motivations for farmers to implement alternative feeds have been studied and appear to vary depending on the livestock (e.g., fish, poultry and pigs are the livestock where animal feed alternatives have the highest acceptance; whereas for grassfed livestock, feed substitution may be more sensitive and only applicable where additional feed is required); acceptance appears to generally be high, although more so for direct waste feedstocks than for insects.<sup>24</sup> Like many decisions discussed in this paper, the primary decision factor appears to be whether it is a cost-effective decision for the farmer's business to make the change, and whether it produces comparable health and growth in livestock, and therefore the speed of uptake would likely correlate to when / if alternative animal feeds become competitive and comparable with conventional feedstocks. Farmer perception of consumer reaction (and how this is mediated by retailers) would also be critical.

### 3.2.2.5 Likely uptake

Our interpretation of the evidence suggests that this innovation is **moderately likely** to occur. The innovations in alternative proteins and animal feedstocks are at high TRL's and in some cases already commercially available, so technological barriers are not the primary limiting factor. The most significant barrier from the literature is perceived to be acceptance of the alternatives from a behavioural and financial perspective, both for human consumption and animal feed. The required changes in order for the protein transition to occur to a widespread degree would require policy changes and changes to funding and subsidies to numerous industries. Unlike some innovations discussed in this report, the success of this innovation depends upon change from consumers in addition to farmers.

### 3.2.2.6 Confidence in potential for impact

The evidence base on the extent to which a protein transition may occur and its projected impact on land use is mixed. There is a general consensus that some form of protein transition will occur for a combination of reasons, including health, economic and environmental reasons. However, there does not appear to be a consensus on whether human consumption patterns will change to the required degree to have a significant impact on land use. Similarly, the lack of uptake of alternative animal feeds to date could reflect that this transition is unlikely to occur at the magnitude and speed required to have a significant change. Limited quantitative evidence means that there is a wide range of estimates, and an assessment of likely demand shifts for human consumption was out of scope for this study. Therefore the confidence in the potential for impact is deemed to be **low**.

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<sup>23</sup> Simon et al., 2024. *Circular food system approaches can support current European protein intake levels while reducing land use and greenhouse gas emissions*. Available at: <https://www.nature.com/articles/s43016-024-00975-2>

<sup>24</sup> Verbeke et al., 2015. *Insects in animal feed: Acceptance and its determinants among farmers, agriculture sector stakeholders and citizens*. Available at: <https://www.sciencedirect.com/science/article/abs/pii/S0377840115001121>

## 3.2.3 Discussion

There are several discussion points on wider impacts and potential unintended consequences to note:

- **Displacement could occur abroad instead of within the UK.** One of the biggest uncertainties relating to land use impacts of protein transition is whether a reduction in land use would occur within the UK or abroad, specifically as a significant proportion of the UK's livestock are fed food from abroad (primarily soy) which has a multitude of environmental impacts including deforestation. Indeed, the net effect of land use change in environmental terms might be greatest if benefits did fall overseas in deforestation risk locations. Similarly, livestock reared abroad may have worse environmental impacts than domestic so potential displacement by imports needs to be considered if the UK moved to a less meat focused production system but consumer tastes did not change.
- **Land savings are not guaranteed.** The crop areas that are currently used for animal feed may be converted to other agricultural systems for human food production as opposed to being freed up for other purposes such as rewilding or sequestration. The magnitude of change is therefore unlikely to be as significant as some literature suggests.
- **The environmental impacts of cultured meats should be considered.** Whilst some potential alternative proteins have minimal environmental impacts (such as algae cultivation) there are concerns that the increased production of cultured meats could lead to higher electricity demand with potential adverse impacts on land use for renewables or emissions from power generation.

## 3.3 Innovation Area 2: Vertical agriculture

### 3.3.1 Overview of scope

Vertical agriculture is the production of food in controlled-environment multi-storey warehouses. In vertical farming, food yield notionally increases by a factor proportional to the number of additional floors. This means that the amount of food produced per unit of land can be multiple times higher than conventional farming. This can reduce the need for agricultural land to maintain the same food output.

**Scope restrictions:** although vertical livestock farming is technically feasible and market ready (e.g. reportedly implemented in China<sup>25</sup>), it is scoped out because we assess there to be a low likelihood that it would be considered in a UK context due to animal welfare and food safety standards (e.g. regulations concerning livestock exposure to natural light and adequate space<sup>26</sup>).

**Technology readiness and adoption to date:** vertical farming has been commercially successful in the UK for high-value horticultural crops, with UK companies considered world leaders in the sector.<sup>27</sup> One supplier produces 30% of the UK basil produce sold in supermarkets from a site of 0.5 hectares.<sup>28</sup> Hence, the TRL for horticulture is 9 – though in practice it remains the case that it has only been applied at small scale relative to the total market. Despite the high TRL, it is unclear that capital investment required make this a viable economic model for most crops at present.

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<sup>25</sup> <https://www.nytimes.com/2023/02/08/business/china-pork-farms.html> ; <https://www.theguardian.com/environment/2022/nov/25/chinas-26-storey-pig-skyscraper-ready-to-produce-1-million-pigs-a-year>

<sup>26</sup> <https://www.legislation.gov.uk/ukdsi/2007/9780110773612>

<sup>27</sup> Savills, 2023. Can vertical farms compete? Available at: [https://www.savills.co.uk/research\\_articles/229130/343469-0#:~:text=A%20premium%20vertical%20farm%20can,%2Dtech%2C%20closely%20controlled%20system](https://www.savills.co.uk/research_articles/229130/343469-0#:~:text=A%20premium%20vertical%20farm%20can,%2Dtech%2C%20closely%20controlled%20system)

<sup>28</sup> Defra, 2023. Foresight study to compare the relative gains, costs, feasibility and scalability of current and future 'industrial horticulture' models. Available at: <https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=20952>

For arable production, vertical wheat growing has been successfully demonstrated in a trial by a commercial vertical agriculture company.<sup>29</sup> Since this trial was a world first, it demonstrates the relatively low TRL of this technology and that it is still a new and evolving approach.<sup>30</sup> There are no arable crops produced in vertical farms and sold commercially to our knowledge. The TRL of arable growing can thus be said to be between 4-6. As with some horticultural crops, it is also likely that the capital investment required might impact the viability of this mode of production as an economic model even if proven technologically.

## 3.3.2 Potential impact

### 3.3.2.1 How could the innovation potentially affect land use?

Vertical farming has the potential to cause systemic change in agricultural production practices and land use. Vertical growing potentially increases the utilisable growing area by multiple times and reduces losses due to environmental variability in open-field agriculture. This results in more produce output per unit of land area, which can in turn reduce and potentially replace the need for land area to be allocated to open-field agriculture to produce the same total quantity. Further, the diversity of crops produced could be significantly expanded due to the ability to fine-tune growing conditions not possible in open field growing. Food waste can potentially be reduced due to the controlled environment<sup>31</sup> which could further contribute to reduction in land needed to produce the same quantity of food. The summarised impact of change in terms of magnitude, likelihood and speed for the horticulture sector is presented in Table 3-2 (the exclusion of livestock and arable from this table is expanded on in below sections).

### 3.3.2.2 What is the likely impact across different sectors?

The literature reviewed for vertical farming is largely skewed towards horticulture, and this likely reflects the fact horticulture is the most viable sector for implementation. Literature on its impact on arable farming reaches similar conclusions about its theoretical potential,<sup>32</sup> but horticulture is the primary focus of the research and impacts. To our knowledge there is no fundamental difference in the technical approach for arable vs horticultural farming, though it should be acknowledged that the financial models are extremely different (focusing on high value productivity as opposed to large areas of crops), which means that the required market and policy incentives will likewise differ. Even within horticulture, this had led to a focus on specific crops in practice.

Literature on arable vertical farming indicates that it is not feasible within the timescales of this research from an economic perspective. Arable crops are likely to have a low economic competitiveness with existing cheap staple crops, and a high cost : return ratio. One study considered how future energy efficiency improvements and price increases in conventionally produced staple crops could improve profitability of arable crops from vertical farms. Considering indoor wheat growing, it found that it is unlikely to be cost recovering under normal market conditions. Even under an optimistic future scenario of lower costs and higher returns (which may occur due to innovations and efficiencies in energy, and climate change affecting conventionally produced wheat) the cost : returns ratio was estimated at ~6:1, indicating it would still not be commercially viable. The implications of this study are that arable vertical farming is highly unlikely to become economically viable prior to 2050. In light of this, arable vertical farming has been scoped out of this work.

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<sup>29</sup> <https://www.infarm.com/news/Infarm-demonstrates-potential-of-indoor-grown-wheat>

<sup>30</sup> Zhu & Marcellis, 2023. Vertical farming for crop production. Available at: <https://library.wur.nl/WebQuery/wurpubs/fulltext/639319>

<sup>31</sup> Delden et al., 2021. Current status and future challenges in implementing and upscaling vertical farming systems. Available at: <https://doi.org/10.1038/s43016-021-00402-w>

<sup>32</sup> Oh & Lu, 2022. Vertical farming - smart urban agriculture for enhancing resilience and sustainability in food security. Available at: <https://doi.org/10.1080/14620316.2022.2141666>

**Table 3-2: Expected impact of change from vertical agriculture innovations on the horticultural sector**

Impact	Magnitude	Speed	Likely uptake	Confidence in potential for impact
Scale	Minor	Intermediate	Moderately likely	Medium

### 3.3.2.3 Potential magnitude

**Potential for change:** In an extreme scenario, theoretically, vertical farming could displace the entire UK conventional horticulture sector, freeing up all associated land. This is because it is technically possible for vegetables, leafy greens, herbs, medicinal plants, fruiting crops and root vegetables to be grown at yields multiple times higher than open field farming due to multiple growing layers, reduced waste, and food quality optimisation.<sup>33,34,35</sup> However, vertical farming is typically discussed as viable for production of high value horticultural crops given the high operating and capital costs of vertical farming.<sup>36</sup> For the foreseeable future, the most optimistic scenario is that vertical agriculture displaces a large fraction of the horticultural sector. In practice, the economic model is only likely to work for higher value crops, or where a premium for freshness favours locating farming closer to consumers. Given these and other constraints outlined in Section 3.3.2.4 on Barriers below, this study concludes that the true potential of vertical agriculture on overall land use is relatively **minor**.

**Evidence availability:** The evidence found for quantifying the potential magnitude of land use change that vertical farming could realise is indirect. Potential impact on land use was inferred based on experimental and modelling studies estimating the yield output that could occur in vertical farms for individual crops<sup>37,38,39</sup> and comparing this with conventional farming methods.

**Scope for quantification:** For horticulture, one study that grew lettuce in an upright vertical column in a controlled environment achieved 13.8 times more crop output compared to a horizontal hydroponic system grown in the same environment<sup>40</sup>. Another review pointed to findings of 100 times higher lettuce yields compared to conventional growing.<sup>41</sup> Horticulture crops currently take up an area of 142,244 hectares in the UK<sup>42</sup>, so assuming a yield 20x higher than conventional growing would hypothetically require an area of ~7,000 hectares to meet total horticultural output of the UK and displace the full current area of 142,244 hectares. This a theoretical maximum estimate based on the assumption that vertical horticulture would compete economically with all existing horticultural production, which is unlikely to be the case given that many horticultural crops may not be suited to vertical growing or be economically competitive. It therefore seems reasonable to assume that vertical horticultural production

<sup>33</sup> Sowmya et al., 2024. Recent developments and inventive approaches in vertical farming. Available at: <https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2024.1400787/full>

<sup>34</sup> Oh & Lu, 2022. Vertical farming - smart urban agriculture for enhancing resilience and sustainability in food security. Available at: <https://doi.org/10.1080/14620316.2022.2141666>

<sup>35</sup> Van Gerwey et al., 2021. Vertical Farming: The Only Way Is Up? Available at: <https://www.mdpi.com/2073-4395/12/1/2>

<sup>36</sup> Savills, 2023. Can vertical farms compete? Available at: [https://www.savills.co.uk/research\\_articles/229130/343469-0#:~:text=A%20premium%20vertical%20farm%20can,%2Dtech%2C%20closely%20controlled%20system](https://www.savills.co.uk/research_articles/229130/343469-0#:~:text=A%20premium%20vertical%20farm%20can,%2Dtech%2C%20closely%20controlled%20system)

<sup>37</sup> Oh & Lu, 2022. Vertical farming - smart urban agriculture for enhancing resilience and sustainability in food security. Available at: <https://doi.org/10.1080/14620316.2022.2141666>

<sup>38</sup> Toulaitos et al., 2016. Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. Available at <https://onlinelibrary.wiley.com/doi/abs/10.1002/fes3.83>

<sup>39</sup> Asseng et al., 2020. Wheat yield potential in controlled-environment vertical farms. Available at: [www.pnas.org/cgi/doi/10.1073/pnas.2002655117](http://www.pnas.org/cgi/doi/10.1073/pnas.2002655117)

<sup>40</sup> Toulaitos et al., 2016. Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. Available at: <https://onlinelibrary.wiley.com/doi/abs/10.1002/fes3.83>

<sup>41</sup> Oh & Lu, 2022. Vertical farming - smart urban agriculture for enhancing resilience and sustainability in food security. Available at: <https://doi.org/10.1080/14620316.2022.2141666>

<sup>42</sup> Defra, 2024. Agricultural land use in the United Kingdom. Available at: <https://www.gov.uk/government/statistics/agricultural-land-use-in-the-united-kingdom>

will, in practice, optimistically displace a relatively low area of horticulture production, perhaps less than 50% of the total horticultural area (less than ~70,000 hectares).

Considering that vertical farms can operate in urban areas, they could avoid the need for productive rural land to be allocated to them. One UK Parliament note published in October 2023 stated that "Calculations from Intelligent Growth Solutions and the James Hutton Institute demonstrate that using 33-35% (11,158–17,774 hectares) of derelict land to build vertical farms could provide every adult in the UK with 5-a-day".<sup>43</sup> However, high costs of urban land might actually make vertical farming more economically feasible away from urban centres where land is comparatively cheaper.<sup>44</sup>

### 3.3.2.4 Barriers

There are multiple barriers that would prevent this innovation from realising its maximum potential effect on agricultural land use. These include:

#### Economic investment factors:

- High energy requirements: requiring 38.8kWh per kg of produce compared to 5.4kWh per kg for greenhouses on average, and the associated cost that can reduce or undermine profitability,<sup>45</sup> and make a unit increase in energy costs far more economically detrimental to vertical agriculture than to conventional agriculture. There is a high demand for artificial lighting and cooling given the need to constantly control the indoor environment and the lack of exposure to natural light. Literature indicates that there is scope for substantial energy efficiency gains<sup>46 47 48</sup> that could reduce this burden, energy demand will always be a challenge compared to open-field agriculture due to the physical constraints of vertical growing.
- Up-front capital requirements: the cost per square metre for a high tech, premium vertical farm is £3000, which can cost up to 750% more than a basic glasshouse.<sup>49</sup> Additionally, labour costs are likely to differ substantially to conventional agriculture given the need for a skilled workforce with specialised technical expertise.
- The need to grow high-market-value crops given the cost of vertical farming, which may preclude its price competitiveness for most foods and limit its adoption at scale. One review discusses vertical farming allowing for the servicing of niche markets and employing long-tail business strategies , supporting this view;

#### Technical constraints:

- Feedback during report drafting suggested that vertical farming is likely to require plant protection methods and high hygiene standards at very high costs, or that it may fail to maintain the levels of yields seen in some pilots as pests and diseases adapt rapidly to the new format. Although one review noted that while the sensitivity of vertical farming to plant pests and

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<sup>43</sup> Bradshaw & Wentworth, 2023. Future of Horticulture. Available at: <https://researchbriefings.files.parliament.uk/documents/POST-PN-0707/POST-PN-0707.pdf>

<sup>44</sup> Savills, 2023. Can vertical farms compete? Available at: [https://www.savills.co.uk/research\\_articles/229130/343469-0#:~:text=A%20premium%20vertical%20farm%20can,%2Dtech%2C%20closely%20controlled%20system](https://www.savills.co.uk/research_articles/229130/343469-0#:~:text=A%20premium%20vertical%20farm%20can,%2Dtech%2C%20closely%20controlled%20system)

<sup>45</sup> Defra, 2023. Foresight study to compare the relative gains, costs, feasibility and scalability of current and future 'industrial horticulture' models. Available at: <https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=20952>

<sup>46</sup> Defra, 2023. Foresight study to compare the relative gains, costs, feasibility and scalability of current and future 'industrial horticulture' models. Available at: <https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=20952>

<sup>47</sup> Engler & Krarti, 2021. Review of energy efficiency in controlled environment agriculture. Available at: [Review of energy efficiency in controlled environment agriculture - ScienceDirect](https://www.sciencedirect.com/science/article/abs/pii/S0959652621000000)

<sup>48</sup> Kaiser et al., 2024. Vertical farming goes dynamic: optimizing resource use efficiency, product quality, and energy costs. Available at: <https://www.frontiersin.org/journals/science/articles/10.3389/fsci.2024.1411259/full>

<sup>49</sup> Savills, 2023. Can vertical farms compete? Available at: [https://www.savills.co.uk/research\\_articles/229130/343469-0#:~:text=A%20premium%20vertical%20farm%20can,%2Dtech%2C%20closely%20controlled%20system](https://www.savills.co.uk/research_articles/229130/343469-0#:~:text=A%20premium%20vertical%20farm%20can,%2Dtech%2C%20closely%20controlled%20system)

diseases is unknown, it anticipated a lower disease pressure due to the ability to fully control the indoor environment and the ability to avoid humans entering the farms through farm automation.<sup>50</sup>

- A limited range of foods can be grown profitably or with consistent or acceptable quality in artificial conditions.<sup>51</sup>

Vertical agriculture may well be practised more by actors coming from outside the traditional farming sector (e.g. technology) and be applied in locations that are not necessarily agricultural at the moment (e.g. more urban settings, brownfield sites). It is therefore potentially a disruptive technology – but as indicated above, may be limited in scale even over the longer term. More traditional models of covered agriculture (e.g. glasshouses) were not a feature of this research as they are not truly 'innovative'. They are more likely to be adopted in traditional farming businesses – but also suffer from some of the same barriers as vertical farming (such as investment costs) albeit to a lesser extent.

### 3.3.2.5 Potential Speed

The evidence indicates that this innovation (and consequent projected impact of land use) is likely to occur at an **intermediate** rate for horticulture. One market research report indicates that growth of the UK industry could be ~24% CAGR between 2022-2027, in line with an estimate at the global level for 2024-2032 of 28.1%.<sup>52 53</sup> As little information was freely available on the existing extent of the vertical farming industry in the UK, it is difficult to estimate an absolute extent of production using these growth rates. However, assuming that 30% of UK basil sold in supermarkets is currently produced via vertical farming, assuming a CAGR of 24% per year, and that this roughly corresponds to growth in production, this implies that horticultural production in vertical farms could supply 100% of the UK produce of ~7-8 different horticultural crops in the **2030-2040s**, dependent on substantial investment in the sector. However, its ultimate impact on horticultural land use is dependent on many factors like the demand for horticultural produce and cost competitiveness of vertically farmed produce.

### 3.3.2.6 Likely uptake

We conclude that this innovation is **moderately likely** to occur, given that it is already commercially successful in the UK and that the evidence reviewed suggests that it is projected to continue growing as an industry in the coming years. Many of the barriers to more widespread adoption can be reduced: high capital costs could be reduced by considering cost effective real estate for siting farms and favourable financial settings, e.g. freeports<sup>54</sup>, however capital costs appear likely to be a persistent challenge due to the need to secure appropriate real estate and high-tech equipment and expertise. Energy requirements have much potential for efficiency gains especially with dynamic environmental condition adjustments aided by smart systems and economies of scale, and co-location next to cheap

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<sup>50</sup> Delden et al., 2021. Current status and future challenges in implementing and upscaling vertical farming systems. Available at: <https://doi.org/10.1038/s43016-021-00402-w>

<sup>51</sup> Delden et al., 2021. Current status and future challenges in implementing and upscaling vertical farming systems. Available at: <https://doi.org/10.1038/s43016-021-00402-w>

<sup>52</sup> Fortune Business Insights, 2024. Vertical Farming Market Size, Share & Industry Analysis, By Type (Hydroponics, Aeroponics, and Aquaponics), By Structure (Building-Based Vertical Farms and Shipping-Container Vertical Farms), By Component (Lighting System, Irrigation and Fertigation System, Climate Control, Sensors, and Others), and Regional Forecast, 2024-2032. Available at: <https://www.fortunebusinessinsights.com/industry-reports/vertical-farming-market-101958>

<sup>53</sup> Actual Market Research, 2022. United Kingdom (UK) Vertical Farming Market Research Report, 2027. Available at: <https://www.actualmarketresearch.com/product/uk-vertical-farming-market>

<sup>54</sup> Savills, 2023. Can vertical farms compete? Available at: [https://www.savills.co.uk/research\\_articles/229130/343469-0#:~:text=A%20premium%20vertical%20farm%20can,%2Dtech%2C%20closely%20controlled%20system](https://www.savills.co.uk/research_articles/229130/343469-0#:~:text=A%20premium%20vertical%20farm%20can,%2Dtech%2C%20closely%20controlled%20system)

and abundant/waste energy sources.<sup>55 56 57</sup> However, the fundamental physical constraints of indoor growing (such as lack of exposure to natural light and the need for continuous environmental control) appears likely to impose high energy demand compared to conventional growing in perpetuity.

Overall, the successful scale-up of this industry in order to compete with conventional food production would require the corresponding scale-up of a high-tech industry with significant capex and OpEx costs, a skilled technical workforce, access to land for new developments, and price competitiveness with conventional growing despite significantly higher input costs. It is therefore considered unfeasible that vertical agriculture will displace the entire horticultural sector for the foreseeable future, but it is considered likely that it will continue to scale up and supplement its production. Given all the above, it seems reasonable to assume that vertical horticultural production will, in practice, displace a relatively low area of horticulture production less than 100,000 hectares.

### 3.3.2.7 Confidence in Potential for Impact

The evidence reviewed on the potential for vertical agriculture agrees on the theoretical potential for it to disrupt conventional food production.<sup>58 59 60 61</sup> However, we found no studies that directly attempt to quantify its impact on land use. Our extrapolation to the potential for disruption of UK land use is principally based on the yield potential of vertical farming relative to conventional growing. Given the economic constraints, we do not consider this theoretical exercise to be reflective of the actual potential of vertical agriculture.

There is little discussion in the literature on the practical and implementation barriers to arable growing in vertical farms, but one study modelled its economic feasibility, which is the principal source for our assessment that it is unlikely to scale up.<sup>62</sup> For horticulture, the various barriers discussed are generally agreed upon among multiple sources.<sup>63 64 65</sup>

Taken together, we consider the confidence in our assessment of speed and magnitude to be **Medium** given the combination of literature reviews, model forecasts, and industry experience and economic forecasting.

## 3.3.3 Discussion

There are several discussion points on wider impacts and potential unintended consequences to note:

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<sup>55</sup> Savills, 2023. Can vertical farms compete? Available at: [https://www.savills.co.uk/research\\_articles/229130/343469-0#:~:text=A%20premium%20vertical%20farm%20can,%2Dtech%2C%20closely%20controlled%20system](https://www.savills.co.uk/research_articles/229130/343469-0#:~:text=A%20premium%20vertical%20farm%20can,%2Dtech%2C%20closely%20controlled%20system)

<sup>56</sup> Engler & Krarti, 2021. Review of energy efficiency in controlled environment agriculture. Available at: [Review of energy efficiency in controlled environment agriculture - ScienceDirect](#)

<sup>57</sup> Kaiser et al., 2024. Vertical farming goes dynamic: optimizing resource use efficiency, product quality, and energy costs. Available at: <https://www.frontiersin.org/journals/science/articles/10.3389/fsoci.2024.1411259/full>

<sup>58</sup> Delden et al., 2021. Current status and future challenges in implementing and upscaling vertical farming systems. Available at: <https://doi.org/10.1038/s43016-021-00402-w>

<sup>59</sup> Oh & Lu, 2022. Vertical farming - smart urban agriculture for enhancing resilience and sustainability in food security. Available at: <https://doi.org/10.1080/14620316.2022.2141666>

<sup>60</sup> Sowmya et al., 2024. Recent developments and inventive approaches in vertical farming. Available at: <https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2024.1400787/full>

<sup>61</sup>

Zhu & Marcelis, 2023. Vertical farming for crop production. Available at: <https://library.wur.nl/WebQuery/wurpubs/fulltext/639319>

<sup>62</sup> Asseng et al., 2020. Wheat yield potential in controlled-environment vertical farms. Available at: [www.pnas.org/cgi/doi/10.1073/pnas.2002655117](http://www.pnas.org/cgi/doi/10.1073/pnas.2002655117)

<sup>63</sup> Sowmya et al., 2024. Recent developments and inventive approaches in vertical farming. Available at: <https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2024.1400787/full>

<sup>64</sup> van Gerrewey et al., 2021. Vertical Farming: The Only Way Is Up?. Available at: <https://www.mdpi.com/2073-4395/12/1/2>

<sup>65</sup> Oh & Lu, 2022. Vertical farming - smart urban agriculture for enhancing resilience and sustainability in food security. Available at: <https://doi.org/10.1080/14620316.2022.2141666>

- High energy demand can contribute to energy scarcity and have wider environmental impacts. The literature discusses the need for renewable, cheap and abundant energy to avoid GHG emissions, but decarbonising the energy source can come with wider environmental trade-offs that need to be weighed up, such as high land use impacts of solar and wind for example.

## 3.4 Innovation Area 3: Precision Agriculture Technologies

### 3.4.1 Overview of scope

Precision agriculture technologies (PAT) account for the spatial and temporal variability of a field to optimise agricultural inputs like fertilisers and fuel, allowing for maintaining existing productivity with lower inputs or increasing productivity with the same inputs<sup>66</sup>, that means less land may be needed for the same output (although feedback during drafting indicated that it is typically associated with the former). This is a broad class of technologies at different levels of development and uptake, different mechanisms, and different implications for agriculture. Key technologies include machine guidance (systems that pilot farm machinery using GPS) that help to avoid farm gaps and overlapping applications<sup>67</sup>. Variable rate application is another class of technologies, notably variable rate nitrogen application (VRN), which allow application of inputs to be targeted to where and when they are needed according to an electronic map or digital readings from sensors.<sup>68</sup> Variable rate irrigation is another example. The technologies could also reduce or create more flexible workloads e.g. by automation but also extending harvest periods by being able to harvest at night.<sup>69</sup>

**Scope Restrictions:** Reviewing the full suite of technologies that fall under PAT in the literature is beyond the scope of this review. It therefore focuses on machine guidance and VRN, which emerged as the technologies that were focused on in-depth in the literature found for PAT.

**Technology readiness and adoption to date:** Machine guidance is a category of smart/automated technologies based on GPS that is constantly evolving. GPS-enabled technology is widespread and used in agricultural machinery, while VRN is also commercially established in the UK<sup>70</sup>, hence both technologies are at TRL 9.

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<sup>66</sup> Soto et al., 2019. The contribution of precision agriculture technologies to farm productivity and the mitigation of greenhouse gas emissions in the EU. Available at:

[https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112505/final\\_technical\\_report\\_pat.pdf](https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112505/final_technical_report_pat.pdf)

<sup>67</sup> Soto et al., 2019. The contribution of precision agriculture technologies to farm productivity and the mitigation of greenhouse gas emissions in the EU. Available at:

[https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112505/final\\_technical\\_report\\_pat.pdf](https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112505/final_technical_report_pat.pdf)

<sup>68</sup> Soto et al., 2019. The contribution of precision agriculture technologies to farm productivity and the mitigation of greenhouse gas emissions in the EU. Available at:

[https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112505/final\\_technical\\_report\\_pat.pdf](https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112505/final_technical_report_pat.pdf)

<sup>69</sup> Soto et al., 2019. The contribution of precision agriculture technologies to farm productivity and the mitigation of greenhouse gas emissions in the EU. Available at:

[https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112505/final\\_technical\\_report\\_pat.pdf](https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112505/final_technical_report_pat.pdf)

<sup>70</sup> Soto et al., 2019. The contribution of precision agriculture technologies to farm productivity and the mitigation of greenhouse gas emissions in the EU. Available at:

[https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112505/final\\_technical\\_report\\_pat.pdf](https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112505/final_technical_report_pat.pdf)

## 3.4.2 Potential impact

### 3.4.2.1 How could the innovation potentially affect land use?

Uptake of machine guidance can lead to higher output on the same area, e.g. through precision seeding that reduces unutilised land on farm and optimises planting distances.<sup>71</sup> This can have indirect effects on plant nutrition and health, as physiological limits imposed by plant competition and lack of access to nutrients when they are most needed are overcome. VRN directly alleviates temporal mismatches between when plants need nutrients the most and when they are available. Our understanding from the literature and informed by subsequent discussion is that VRN is typically used to reduce inputs by farmers while maintaining the same yields, rather than to increase output with the same inputs.

The primary mechanism by which these technologies could affect land use is by reducing the area of land needed for the same total output – using VRN to maintain output per unit area with lower inputs will not achieve this. It is also worth noting that there are undoubtedly physical and physiological limits to the amount of yield gain that can be achieved with these technologies, such that yield increases are likely to occur as a one-off change with the introduction of a given technology. The marginal gain of adding a new technology on farm is likely to diminish over time due to this. Indeed, one study exploring the relationship between PAT adoption and technical efficiency using data from a 2016 survey of US farms found that efficiency gains showed diminishing marginal returns with increasing PAT adoption.<sup>72</sup>

The summarised impact of change in terms of magnitude, likelihood and speed is presented in Table 3-3.

### 3.4.2.2 What is the likely impact across different sectors?

Literature on yield impacts of PAT uptake were found for arable growing. No definitive estimates of yield changes with PAT uptake in livestock or horticultural systems were found.

**Table 3-3: Expected impact of change from increased productivity of farming innovations**

Impact	Magnitude	Speed	Likely uptake	Confidence in potential for impact
Scale	Minor	Rapid	Likely	Medium

### 3.4.2.3 Potential magnitude

**Potential for change:** The evidence indicates that the magnitude of change in land use because of the implementation of PAT innovations is expected to be **minor** and to cause **incremental** changes to agricultural production practices and land use through a series of step-changes at the individual field level over time as technologies improve (noting that there will certainly be physiological limits to gains that can accrue). Integration of PAT is an ongoing phenomenon in UK farming and does not appear to lead to a fundamental shift in farming approaches. Rather, it aids the efficiency of existing techniques to facilitate marginal gains in productivity or reductions in inputs.

<sup>71</sup> Monteiro et al., 2021. Precision Agriculture for Crop and Livestock Farming—Brief Review. Available at: <https://www.mdpi.com/2076-2615/11/8/2345>

<sup>72</sup> Delay et al., 2021. Precision agriculture technology adoption and technical efficiency. Available at: <https://onlinelibrary.wiley.com/doi/epdf/10.1111/1477-9552.12440>

**Evidence availability:** We found two reputable sources reporting on uptake of PAT technologies in the UK, the Defra Farm Practices Survey from 2012<sup>73</sup> and a European Commission JRC technical report from 2019.<sup>74</sup> With respect to impacts on yield, there was limited information. We found results from one VRN trial reported on the website of a commercial supplier of VRN in the UK<sup>75</sup>, and one study investigating the effect of VRN in a South African context<sup>76</sup> which was scoped out due to lack of applicability to the UK (given the different agri-climatic context). We found one mention of the effect on output of precision seeding in a literature review citing another study<sup>77</sup> but could not access the original paper. There was no accessible literature found on the effect of PAT on land use change.

**Scope for quantification:** To attempt to quantify the likely magnitude of change on land use, we have relied on data reporting changes in crop yields with uptake of PAT as a proxy for its impact on land use, assuming a proportional reduction in land use would occur (total output remains constant). For the adoption of precision seeding, output reportedly increases by 10-30%.<sup>78</sup> Evidence from an industry trial suggests that VRN adoption causes single-digit percentage increases in yields (<5%), with the same company claiming to achieve an average yield increase of 4.65% from VRN application.<sup>79</sup>

The 2012 Defra Farm Practices Survey found that 22% of farms in England used GPS precision farming technologies, with 16% using variable rate application, and 11% use yield mapping.<sup>80</sup> In accordance with the survey conducted by Soto et al. (2019), rates of adoption generally increased with farm size. Considering the Soto et al. (2019) findings of ~30% and ~45% uptake of machine guidance and VRN technologies respectively, this represents a 36% increase in machine guidance uptake and a 2.8-fold increase in VRN uptake in less than a decade. Comparing yields in UK cereal for different five-year intervals between 2004-2023, there is no persistent step increase in yields observed over time, and the difference between the time intervals with highest (2015-2019) and lowest (2010-2014) yield values is a difference of 7% (Table 3-4). Furthermore, the within year variability of each time interval (shown by the standard deviations in Table 3-4) represents at most a change of 8.2% relative to the average for the time interval. Assuming the survey results for uptake of PAT in UK agriculture apply to cereal crops, the single digit increases in output per unit land area over the 2010s decade suggests that uptake of PAT had low to negligible effects on yield (notwithstanding that yield increases over years could have been influenced by a multitude of other factors like climate changes, selective breeding etc, and year-to-year variability will also impact real world performance). Therefore, we might expect further widespread adoption of PAT may, at best, result in single digit increases in yield.

Assuming further adoption of PAT causes a 2% increase in agricultural yields across the UK every decade, by 2045 this would translate into a reduction of the required agricultural land to maintain the same total output of ~170,000 hectares. A very optimistic estimate would be a 4% yield increase per decade resulting in ~339,000 hectares that could be displaced.

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<sup>73</sup> Defra, 2013. Farm practices survey October 2012 - current farming issues. Available at:

<https://www.gov.uk/government/statistics/farm-practices-survey-october-2012-current-farming-issues>

<sup>74</sup> Soto et al., 2019. The contribution of precision agriculture technologies to farm productivity and the mitigation of greenhouse gas emissions in the EU. Available at:

[https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112505/final\\_technical\\_report\\_pat.pdf](https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112505/final_technical_report_pat.pdf)

<sup>75</sup> Jones, 2022. Enhancing farm efficiency with variable rate nitrogen – What do the latest trials results tell us? Available at:

<https://www.frontierag.co.uk/blog/enhancing-farm-efficiency-with-variable-rate-nitrogen-what-do-the-latest-trials-results-tell-us>

<sup>76</sup> Maine et al., 2010. Impact of variable-rate application of nitrogen on yield and profit: a case study from South Africa. Available at: <https://link.springer.com/article/10.1007/s11119-009-9139-8>

<sup>77</sup> Monteiro et al., 2021. Precision Agriculture for Crop and Livestock Farming—Brief Review. Available at:

<https://www.mdpi.com/2076-2615/11/8/2345>

<sup>78</sup> Monteiro et al., 2021. Precision Agriculture for Crop and Livestock Farming—Brief Review. Available at:

<https://www.mdpi.com/2076-2615/11/8/2345>

<sup>79</sup> Jones, 2022. Enhancing farm efficiency with variable rate nitrogen – What do the latest trials results tell us? Available at:

<https://www.frontierag.co.uk/blog/enhancing-farm-efficiency-with-variable-rate-nitrogen-what-do-the-latest-trials-results-tell-us>

<sup>80</sup> Defra, 2013. Farm practices survey October 2012 - current farming issues. Available at:

<https://www.gov.uk/government/statistics/farm-practices-survey-october-2012-current-farming-issues>

**Table 3-4: Wheat yields of UK wheat and barley<sup>81</sup>**

Time interval	Mean cereal yield (t/ha)	Cereal yield standard deviation (+/-)
2005 – 2009	7.1	0.30
2010 – 2014	6.9	0.55
2015 – 2019	7.4	0.54
2020 – 2023	7.0	0.58

### 3.4.2.4 Barriers

The Soto et al. (2019) survey investigated the barriers to further uptake of GPS and VRN by farmers. Their findings included:

- high investment cost and long payback periods. This risks increasing the financial barriers to entry and economic sustainability for farmers;
- uncertainty related to potential positive impacts of the technologies and hence the potential for return on investment;
- farm size: adoption is skewed towards larger farms that may have more resources to experiment and benefit from economies of scale with incremental gains. Similar conclusions were drawn in the US study of PAT adoption and technical efficiency gains mentioned above.<sup>82</sup>;
- farmer age (older farmers less likely to adopt PAT).

### 3.4.2.5 Potential speed

The evidence indicates that this innovation is likely to occur at a **rapid** rate, because the PAT is already widespread in UK agriculture in various forms, with the science on how to improve them advancing in a large and increasing body of literature.<sup>83</sup> Further, the surveys over the past decade indicate that a rapid uptake has occurred already, and there is no apparent obvious reason why this should not continue going forward. In our view, it is likely that as the technologies improve/new tech is created, there will be greater price flexibility and a wider range of applicability to different farm contexts for the adoption of PAT (e.g. drones can be useful regardless of farm size). Further, as older generations of farmers are replaced by younger ones that may be more inclined to experiment with new technologies, and the science and industry awareness on the benefits of adoption of PAT continues to develop, it is likely that PAT will continue to be integrated into UK agriculture.

<sup>81</sup> <https://www.gov.uk/government/statistics/agriculture-in-the-united-kingdom-2023/chapter-7-crops>

<sup>82</sup> Delay et al., 2021. Precision agriculture technology adoption and technical efficiency. Available at: <https://onlinelibrary.wiley.com/doi/epdf/10.1111/1477-9552.12440>

<sup>83</sup> Monteiro et al., 2021. Precision Agriculture for Crop and Livestock Farming—Brief Review. Available at: <https://www.mdpi.com/2076-2615/11/8/2345>

### 3.4.2.6 Likely uptake

The evidence indicates that this innovation is **likely** to occur. The identified barriers to implementation do not appear to impose fundamental limits on uptake. PAT uptake has a strong historical precedent in the UK, with PAT technologies widely accepted in UK farming as indicated by the surveys outlined above. The prevailing barriers can be overcome with appropriate financing, education, changing farmer demographics, and continued technological improvements. However, as per the discussion above, rapid uptake does not necessarily translate into rapid uptake for the purpose of yield enhancement (with corresponding land use impacts) but may be more about input efficiency and a desire to reduce potential environmental pollution. We did not find any literature investigating how these two farmer motivations for adopting PAT might lead to different yield outcomes.

### 3.4.2.7 Confidence in potential for impact

We have a **medium** confidence in the assigned potential for impact of PAT. This is because of the survey data available that provide a clear indication of PAT uptake, as well as historical trends in crop yields that provide an indication of its potential effect on crop yield over time, allowing us to draw inferences on its effect on the land use efficiency of farming. The adoption of PAT is also evidenced to be common in UK agriculture with a large growth in adoption in the past, and we found no reason to suspect that this trend should not continue going forward. However, there is a low amount of academic literature providing data on the changes in crop yields with adoption of PAT technologies in a UK context, and no literature was found explicitly modelling or assessing the impact of PAT uptake on land use. Taken together, we believe that medium confidence in our assessment is appropriate.

## 3.4.3 Discussion

There are a few discussion points on wider impacts and potential unintended consequences to note:

- Uptake of these technologies is perhaps more likely as a means to primarily realise input efficiencies that to increase yields.
- Increase in land use efficiency may not translate into a lower land footprint if farmers decide to increase food output across the same area of farmland to maximise profitability (especially with an economic incentive to do so).
- Higher input efficiencies can have a wide range of environmental benefits (discussed in Section 3.1) and can improve socioeconomic resilience of farms due to less dependence on potentially volatile farm input prices, regardless of land use impact.

## 3.5 Innovation Area 4: Genetic technologies

### 3.5.1 Overview of scope

Genetic technologies (GT) are a broad class of technologies, some of which are well established and some are still in development, with different mechanisms of action and implications for food production. These include:

- **Gene editing**, in which specific traits are turned on or off at the genetic level using gene editing technologies like CRISPR, e.g. traits that inhibit growth or result in susceptibility to pests/disease.<sup>84</sup>
- **Gene drives**, referring to a GT approach that ensures that all of the offspring of a gene-edited organism take on the edited traits through conventional reproduction<sup>85</sup>.
- **Genetic modification (GMO)** refers to the artificial alteration of an organisms DNA by inserting a piece of foreign DNA into their genome.<sup>86</sup>
- **Selective breeding**, which entails breeding organisms with desirable traits (e.g. cows with high milk production) to cause changes to traits in the offspring in the desired direction. This practice has been ongoing for decades if not millennia in human history but has been augmented in the modern era with improved breeding tools and greater scientific understanding and mathematical models to predict desired outcomes.<sup>87</sup>

**Scope Restrictions:** though gene drives have the potential to disrupt the food system, as of 2021, gene drives were making significant progress in laboratory settings but were still at proof-of-concept stage rather than implemented.<sup>88</sup> We have therefore scoped them out of this review. Also note that while this section discusses recent regulations on gene editing, we have not considered the regulatory landscape for other genetic technologies (gene editing regulation is discussed due to its recent reform that has significant implications for the evolution and uptake of genetic technologies in the UK).

**Technology readiness and adaption to date:** genetically modified foods have been in commercial use for 30 years<sup>89</sup> and have a long history of successful sale in the UK.<sup>90</sup> Various bioengineered crops are commercially successful in the US, Canada, Brazil and other countries, such as herbicide-tolerant canola and insect resistant corn.<sup>91</sup> In the UK, the chief scientist at Defra indicated in 2022 that gene-edited crops are five years away from being sold in the UK market<sup>92</sup>, prior to new regulations being passed in 2023 in the Precision Breeding Act which facilitate bringing crops that have been modified with genetic technologies to public use.<sup>93</sup> Furthermore, a 3-year, £2.2 million project funded by the Farming Innovation Programme called PROBITY will grow three genetically edited cereal crops on up to 25 farms in England in the 2025/26 cropping season, including a wheat with a bigger grain size with the goal of causing a step-change in productivity.<sup>94</sup> Bioengineered crops are therefore close to being ready for commercial deployment in the UK. However, it is important to note that the Precision Breeding Act facilitates the use of modern biotechnology for producing genetic changes that could have arisen through natural breeding. This does not allow for mixing genes between sexually incompatible species, and therefore provides a limit on the amount and rate of improvement that can be achieved.

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<sup>84</sup> Massel, 2023. What's the latest on GMOs and gene-edited foods – and what are the concerns? An expert explains. Available at: <https://theconversation.com/whats-the-latest-on-gmos-and-gene-edited-foods-and-what-are-the-concerns-an-expert-explains-204275>

<sup>85</sup> Clapp & Ruder, 2020. Precision Technologies for Agriculture: Digital Farming, Gene-Edited Crops, and the Politics of Sustainability. Available at: <https://direct.mit.edu/glep/article/20/3/49/95048/Precision-Technologies-for-Agriculture-Digital>

<sup>86</sup> Massel, 2023. What's the latest on GMOs and gene-edited foods – and what are the concerns? An expert explains. Available at: <https://theconversation.com/whats-the-latest-on-gmos-and-gene-edited-foods-and-what-are-the-concerns-an-expert-explains-204275>

<sup>87</sup> de Haas et al., 2021. Selective breeding as a mitigation tool for methane emissions from dairy cattle. Available at: <https://www.sciencedirect.com/science/article/pii/S1751731121001373>

<sup>88</sup> Bier, 2021. Gene drives gaining speed. Available at: <https://www.nature.com/articles/s41576-021-00386-0>

<sup>89</sup> Royal Society, 2023. Enabling genetic technologies for food security POLICY BRIEFING. Available at: <https://royalsociety.org/-/media/policy/projects/gene-tech/genetically-modified-organisms-regulation-policy-briefing.pdf>

<sup>90</sup> UK Parliament Post, 1998. GENETICALLY MODIFIED FOODS - Parliament post. <https://www.parliament.uk/globalassets/documents/post/pn115.pdf>

<sup>91</sup> USDA, 2024. List of Bioengineered Foods. Available at: <https://www.ams.usda.gov/rules-regulations/be/bioengineered-foods-list>

<sup>92</sup> <https://www.newscientist.com/article/2305284-gene-edited-food-is-5-years-away-in-england-says-government-scientist/>

<sup>93</sup> Royal Society, 2023. Enabling genetic technologies for food security POLICY BRIEFING. Available at: <https://royalsociety.org/-/media/policy/projects/gene-tech/genetically-modified-organisms-regulation-policy-briefing.pdf>

<sup>94</sup> <https://bofin.org.uk/probity/>

## 3.5.2 Potential impact

### 3.5.2.1 How could the innovation potentially affect land use?

Genetic technologies are employed to create new strains with favourable genetic traits, or to eliminate unfavourable genes that hinder the organism's vitality or productivity. These technologies could be used not just to increase yields, but also to increase organism resistance to pests or diseases, herbicides, improve input utilisation, or the ability to effectively utilise more variable quality inputs. These factors could directly and indirectly translate into higher crop yields over a given area as less crop is lost to environmental factors and/or each organism has a higher output per unit input. This means that less land would be needed to produce the same total food output, and a reduction in land use can occur. The summarised impact of change in terms of magnitude, likelihood and speed is presented in Table 3-5.

### 3.5.2.2 What is the likely impact across different sectors?

Literature was found documenting increases in yields and economic gains associated with genetic improvement for both plant and animal breeding. These include analysis of historic patterns in yield improvement since the mid-to-late 20<sup>th</sup> century associated with selective breeding techniques and genetic modification.<sup>95 96 97 98</sup> These results imply that significant improvements in yields are likely in arable and horticultural as well as livestock production. More detail is provided in Section 3.5.2.3 on Potential magnitude below.

**Table 3-5: Expected impact of change from genetic technologies**

Impact	Magnitude	Speed	Likely uptake	Confidence in potential for impact
Scale	Significant	Intermediate	Likely	Medium

### 3.5.2.3 Potential magnitude

**Potential for change:** The evidence indicates that the magnitude of change in land use as a result of the implementation of genetic technology innovations is expected to be **significant**. This innovation is expected to manifest as yield efficiency gains that accumulate over years as minor phenotypic changes accrue from targeted gene edits or improved precision breeding over multiple reproductive generations. Cumulative gains over time are especially likely in livestock, considering that continuous yield improvements have been observed over the past six decades in dairy cattle breeds in Canada

<sup>95</sup> Pellegrino et al., 2021. Impact of genetically engineered maize on agronomic, environmental and toxicological traits: a meta-analysis of 21 years of field data. Available at: <https://www.nature.com/articles/s41598-018-21284-2>

<sup>96</sup> Mackay et al., 2010. Reanalyses of the historical series of UK variety trials to quantify the contributions of genetic and environmental factors to trends and variability in yield over time. Available at: [https://www.researchgate.net/profile/Ian-Mackay-6/publication/46221322\\_Reanalyses\\_of\\_the\\_historical\\_series\\_of\\_UK\\_variety\\_trials\\_to\\_quantify\\_the\\_contributions\\_of\\_genetic\\_and\\_environmental\\_factors\\_to\\_trends\\_and\\_variability\\_in\\_yield\\_over\\_time/links/02e7e521cd64106dea000000/Reanalyses-of-the-historical-series-of-UK-variety-trials-to-quantify-the-contributions-of-genetic-and-environmental-factors-to-trends-and-variability-in-yield-over-time.pdf](https://www.researchgate.net/profile/Ian-Mackay-6/publication/46221322_Reanalyses_of_the_historical_series_of_UK_variety_trials_to_quantify_the_contributions_of_genetic_and_environmental_factors_to_trends_and_variability_in_yield_over_time/links/02e7e521cd64106dea000000/Reanalyses-of-the-historical-series-of-UK-variety-trials-to-quantify-the-contributions-of-genetic-and-environmental-factors-to-trends-and-variability-in-yield-over-time.pdf)

<sup>97</sup>

Mueller & van Eenennaam, 2022. Synergistic power of genomic selection, assisted reproductive technologies, and gene editing to drive genetic improvement of cattle. Available at: <https://cabiaqbio.biomedcentral.com/articles/10.1186/s43170-022-00080-z>

<sup>98</sup> AbacusBio, 2022. A vision for improving the UK sheep and beef sectors through breeding over the next 10 years. Available at: <https://ahdb.org.uk/scoping-study-delivering-a-vision-for-improving-the-beef-and-sheep-sectors-through-animal-breeding-over-the-next-ten-years>

and the US that are linked to genetic improvement.<sup>99</sup> This seems likely to be similar for crops considering that there is a wide variety of gene edited crops that are ready for commercialisation having received regulatory approval, or are already commercialised in other countries<sup>100</sup>, in combination with the continuously developing body of literature of experimentation gene editing in crops<sup>101</sup>, providing scope for continuous implementation of new approaches going forward.

A 2022 report for Defra and the AHDB on genetic improvement in the beef and sheep sectors conducted interviews with multiple industry stakeholders in the genetics industry including breeding companies, livestock specialists and farmers.<sup>102</sup> It found that most respondents answered 'yes' to the question of whether improved genetics can help address their biggest business challenges in the next 5-10 years or deliver value in other areas. This indicates that there is a willingness by industry stakeholders to implement genetic technologies in the foreseeable future, further motivating the expectation that genetic technologies could have a significant impact in the livestock sector going forward.

There is likely to be physiological upper limits to the amount of gain that can be achieved, such that gains from introducing a new genetic change may diminish and eventually cease after a time.

### Scope for quantification:

**Livestock:** The historic economic gains from selective breeding of livestock was modelled in the 2022 report for Defra and the AHDB, which claimed that "*the historic rate of genetic gain will deliver annualised benefits of £14.7m (net present value [NPV] or £183.2m over the next 20 years) and £6.8 (NPV of £84m over the next 20 years) for sheep and beef, respectively.*"<sup>103</sup> While no UK-specific data on the livestock yield gains from genetic technologies over time was found, given the universality of the genetic approaches, patterns observed in other countries can be generalised. Compared to 1944, the US dairy cattle herd as of 2017 produced ~80% more milk with ~65% less cows due to a >4x increase in milk production per cow, with estimates that roughly half of this gain (2x) is attributable to genetic gains associated with artificial insemination.<sup>104</sup> This improvement has come about with considerable declines in resources needed. A comparison of US dairy production systems in 2007 relative to 1944 shows that animal energy requirements per billion kg of milk produced in 2007 was 23% of its value in 1944, as is the case for quantity of feedstuffs required.<sup>105</sup> For land area, this value is 9.5%, while similar double-digit percent declines are seen for water, waste output, and greenhouse gas emissions. These metrics have generally seen further double-digit percentage declines when comparing 2017 to 2007.<sup>106</sup> However it is important to note that the US livestock system is more intensive than that of the UK, with industrial confined animal feeding systems being widely used<sup>107</sup>, so that the improvements for some metrics may be relatively less pronounced in a UK context (e.g. land).

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<sup>99</sup> Brito et al., 2021. Review: Genetic selection of high-yielding dairy cattle toward sustainable farming systems in a rapidly changing world. Available at: <https://www.sciencedirect.com/science/article/pii/S175173112100135X>

<sup>100</sup> Polidoros et al., 2024. Genome-Editing Products Line up for the Market: Will Europe Harvest the Benefits from Science and Innovation? Available at: <https://pmc.ncbi.nlm.nih.gov/articles/PMC11353485/>

<sup>101</sup> <https://bofin.org.uk/probity/>

<sup>102</sup> AbacusBio, 2022. A vision for improving the UK sheep and beef sectors through breeding over the next 10 years. Available at: <https://ahdb.org.uk/scoping-study-delivering-a-vision-for-improving-the-beef-and-sheep-sectors-through-animal-breeding-over-the-next-ten-years>

<sup>103</sup> AbacusBio, 2022. A vision for improving the UK sheep and beef sectors through breeding over the next 10 years. Available at: <https://ahdb.org.uk/scoping-study-delivering-a-vision-for-improving-the-beef-and-sheep-sectors-through-animal-breeding-over-the-next-ten-years>

<sup>104</sup> Mueller & van Eenennaam, 2022. Synergistic power of genomic selection, assisted reproductive technologies, and gene editing to drive genetic improvement of cattle. Available at: <https://cabiaqbio.biomedcentral.com/articles/10.1186/s43170-022-00080-z>

<sup>105</sup> Capper et al., 2009. The environmental impact of dairy production: 1944 compared with 2007. Available at: <https://academic.oup.com/jas/article/87/6/2160/4731307>

<sup>106</sup> Capper & Cady, 2020. The effects of improved performance in the U.S. dairy cattle industry on environmental impacts between 2007 and 2017. Available at: <https://academic.oup.com/jas/article/98/1/skz291/5581976>

<sup>107</sup> Kleppel, 2020. Do Differences in Livestock Management Practices Influence Environmental Impacts? Available at: <https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2020.00141/full>

It seems plausible that the application of more advanced and precise genetic technologies (like gene editing) when applied to livestock could achieve similar magnitudes of efficiency gains across different livestock food production systems, translating into proportional reductions in land use of this sector.

**Arable & horticulture:** One estimate is that genetic improvement was responsible for effectively all of the increases in yield in winter wheat, winter barley, and spring barley in the UK between 1982-2007 (from ~6.2 to 8.1t/ha, ~5.5 to 6.5t/ha, and ~4.6-5.5t/ha i.e. in the ballpark of ~5-30% increase).<sup>108</sup> These estimates agree with another meta-analysis of historic maize yield gains associated with genetic modification using a global dataset with 21 years-worth of data that showed average yield increases between 5.6-24.5%.<sup>109</sup> Similar magnitudes of change seem likely to occur in future in a UK context, given the wider range of modern precision genetic tools available that can be applied to a wider variety of plant types and the ability to target genes with high precision. We found no literature indicating that there are any major differences in the application of genetic tools between arable crops and horticultural crops, so we assume similar gains could be achieved in the horticultural sector.

Assuming that similar improvements in yields of various arable crops of 5-30% will occur over a period of 25 years with more sophisticated genetic technology adoption (as was observed between 1982-2007), the area of UK arable and horticultural land required to maintain the same food production would reduce between ~214,000-1.28 million hectares.

### 3.5.2.4 Barriers

There are multiple barriers that would prevent this innovation from occurring, and from the implementation of this innovation leading to the potential maximum change in agricultural land use. These include:

- Negative consumer perceptions: a 2021 survey by the Food Standards Agency of UK consumer perceptions of genome-edited foods found that consumers raised concerns around food safety, animal welfare, regulations and transparency, the question of whether genetic technologies will be used for the benefit of wider society, and environmental impacts.<sup>110</sup> Consumers viewed GMO or genetically edited plants as safer to consume than genetically edited animals.
- Regulatory barriers: although these have been improved with the Precision Breeding Act, 2023, the law still requires that any engineered genetic changes are those that could have occurred in nature or via traditional breeding methods<sup>111</sup>, imposing regulatory constraints on the innovation cycle and ultimately the rate at which new strains can be brought to market.

### 3.5.2.5 Potential speed

The evidence indicates that this innovation (and consequent projected impact of land use) is likely to occur at an **intermediate** rate. The literature reviewed on magnitude of change has shown that these magnitudes have occurred over multiple decades in the case of selective breeding, and for GMO, gains have occurred over two decades. Since gene editing technology is already mature, in the absence of

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<sup>108</sup> Mackay et al., 2010. Reanalyses of the historical series of UK variety trials to quantify the contributions of genetic and environmental factors to trends and variability in yield over time. Available at: [https://www.researchgate.net/profile/Ian-Mackay-6/publication/46221322\\_Reanalyses\\_of\\_the\\_historical\\_series\\_of\\_UK\\_variety\\_trials\\_to\\_quantify\\_the\\_contributions\\_of\\_genetic\\_and\\_environmental\\_factors\\_to\\_trends\\_and\\_variability\\_in\\_yield\\_over\\_time/links/02e7e521cd64106dea000000/Reanalyses-of-the-historical-series-of-UK-variety-trials-to-quantify-the-contributions-of-genetic-and-environmental-factors-to-trends-and-variability-in-yield-over-time.pdf](https://www.researchgate.net/profile/Ian-Mackay-6/publication/46221322_Reanalyses_of_the_historical_series_of_UK_variety_trials_to_quantify_the_contributions_of_genetic_and_environmental_factors_to_trends_and_variability_in_yield_over_time/links/02e7e521cd64106dea000000/Reanalyses-of-the-historical-series-of-UK-variety-trials-to-quantify-the-contributions-of-genetic-and-environmental-factors-to-trends-and-variability-in-yield-over-time.pdf)

<sup>109</sup> Pellegrino et al., 2021. Impact of genetically engineered maize on agronomic, environmental and toxicological traits: a meta-analysis of 21 years of field data. Available at: <https://www.nature.com/articles/s41598-018-21284-2>

<sup>110</sup> FSA, 2021. Consumer perceptions of genome edited food. Available at: <https://www.food.gov.uk/sites/default/files/media/document/consumer-perceptions-of-genome-edited-food.pdf>

<sup>111</sup> Royal Society, 2023. Enabling genetic technologies for food security POLICY BRIEFING. Available at: <https://royalsociety.org/-/media/policy/projects/gene-tech/genetically-modified-organisms-regulation-policy-briefing.pdf>

regulatory or public perception barriers, the uptake of gene editing could technically happen within the next decade, accruing yield benefits within the **2030-2040s** decades.

Ignoring existing gene-edited strains that could be taken up immediately in UK agriculture, 2-3 plant generations are needed for a novel gene-edit to commercialize<sup>112</sup>, meaning that newly created varieties could technically be brought to market in 2-3 years. However, expert input during drafting highlighted that this is unlikely in practice, because it could take ~15 years to bring a new strain to market from the beginning of the innovation cycle due to the need for regulatory approval and clarity of understanding across multiple stakeholders involved throughout the process. For slower breeding livestock, these changes may take longer, for example because more time is needed to introduce changes to an individual into a herd through breeding.

### 3.5.2.6 Likely uptake

The evidence indicates that this innovation is **likely** to occur, though the regulatory environment and related consumer acceptability will be important. There is a strong historical precedent for uptake of genetic technologies given the commercial success of GMO worldwide over the past 2 to 3 decades as well as the long history of selective breeding in agriculture. This suggests that public perception barriers can be readily overcome. Indeed, the 2021 Food Standards Agency survey found that after participants became informed about genome editing, there was a shift towards greater acceptance.<sup>113</sup> Given that gene editing already exists as a mature technology, the regulatory reform occurring with the Precision Breeding Act in 2023 has provided an avenue for widespread implementation of gene editing in UK markets. There is incentive for farmers to adopt these technologies given the potential benefits, and no insurmountable barriers were identified. It appears that the rate of uptake would be most constrained by capital costs, rates at which new strains can be produced, and regulatory processes to bring new strains to market.

### 3.5.2.7 Confidence in potential for impact

We have **medium** confidence in our assessment of the potential for impact. While multiple sources point towards genetic technologies causing meaningful increases in agricultural yields<sup>114,115,116</sup>, we found no direct evidence for horticultural crops or livestock yield gains other than for dairy. We found no mention of this being due to these technologies not being applicable to these other forms of produce – it may be that literature focuses on staple agricultural crops over horticultural crops as they are more common and economically important, while the lack of focus on animal genetic engineering may be because it is controversial from an ethics and animal welfare perspective<sup>117</sup> (also note that chicken was scoped out of the research due to minimal land use footprint). Some evidence was not UK specific either, which limits the applicability of the findings. We have assumed that yield gains from GMO and selective breeding would similarly occur for gene editing, which we consider reasonable because using gene edits to increase overall yield is one of the major value propositions of the technology. However, gene editing is fundamentally a different class of technology to GMO and selective breeding, and we have no direct

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<sup>112</sup> Dhugga, 2022. Gene Editing to Accelerate Crop Breeding. Available at: <https://pmc.ncbi.nlm.nih.gov/articles/PMC9196881/>

<sup>113</sup> FSA, 2021. Consumer perceptions of genome edited food. Available at: <https://www.food.gov.uk/sites/default/files/media/document/consumer-perceptions-of-genome-edited-food.pdf>

<sup>114</sup> Mueller & van Eenennaam, 2022. Synergistic power of genomic selection, assisted reproductive technologies, and gene editing to drive genetic improvement of cattle. Available at: <https://cabiagbio.biomedcentral.com/articles/10.1186/s43170-022-00080-z>

<sup>115</sup> Mackay et al., 2010. Reanalyses of the historical series of UK variety trials to quantify the contributions of genetic and environmental factors to trends and variability in yield over time. Available at: [https://www.researchgate.net/profile/Ian-Mackay-6/publication/46221322\\_Reanalyses\\_of\\_the\\_historical\\_series\\_of\\_UK\\_variety\\_trials\\_to\\_quantify\\_the\\_contributions\\_of\\_genetic\\_and\\_environmental\\_factors\\_to\\_trends\\_and\\_variability\\_in\\_yield\\_over\\_time/links/02e7e521cd64106dea000000/Reanalyses-of-the-historical-series-of-UK-variety-trials-to-quantify-the-contributions-of-genetic-and-environmental-factors-to-trends-and-variability-in-yield-over-time.pdf](https://www.researchgate.net/profile/Ian-Mackay-6/publication/46221322_Reanalyses_of_the_historical_series_of_UK_variety_trials_to_quantify_the_contributions_of_genetic_and_environmental_factors_to_trends_and_variability_in_yield_over_time/links/02e7e521cd64106dea000000/Reanalyses-of-the-historical-series-of-UK-variety-trials-to-quantify-the-contributions-of-genetic-and-environmental-factors-to-trends-and-variability-in-yield-over-time.pdf)

<sup>116</sup> Pellegrino et al., 2021. Impact of genetically engineered maize on agronomic, environmental and toxicological traits: a meta-analysis of 21 years of field data. Available at: <https://www.nature.com/articles/s41598-018-21284-2>

<sup>117</sup> Garas et al., 2015. Genetically Engineered Livestock: Ethical Use for Food and Medical Models. Available at: <https://www.annualreviews.org/content/journals/10.1146/annurev-animal-022114-110739>

evidence that similar yield gains may occur. Finally, we found no literature explicitly linking genetic technologies to land use change and have relied on assuming yield gains would translate into proportional changes in land use assuming total production stays constant.

### 3.5.3 Discussion

There are several discussion points on wider impacts and potential unintended consequences to note:

- It has been concluded by the Royal Society London and National Academies of Science, Engineering and Medicine that no evidence exists that using GM techniques to produce new crop varieties is any more likely to produce unforeseen effects (be those environmental, human health related or otherwise) than producing them using conventional cross-breeding.<sup>118 119</sup> However, given the relative novelty of newer GM techniques like CRISPR gene editing and gene drives, the absence of evidence of negative effects does not necessarily mean that negative impacts are not likely. This is because there has been limited time and commercial experience with these techniques to allow for the development of a rigorous body of evidence on their potential adverse impacts. At the other end of the scale, the risks of irreversible ecological change resulting from the introduction of bioengineered organisms (e.g. from gene drives, gene flow to wild populations, adverse effects on non-target organisms) have all been raised as concerns.<sup>120</sup> More prosaically, disease, weed, and animal pests may all evolve rapidly alongside new crops and breeds.
- As discussed for PAT, an increase in land use efficiency may not translate into a lower land footprint if farmers decide to increase food output across the same area of farmland to maximise profitability (especially with an economic incentive to do so).
- Genetic technologies may be adopted for multiple reasons not directly associated with improving yield. The interview results reported in the 2022 report for Defra and the AHDB on genetic improvement in the beef and sheep sectors<sup>121</sup> asked the question “how else could genetic information help your business?”, finding that the most frequent answer was with reference to health traits and environmental impact, second was resilience/longevity and productivity, followed by eating quality and feed conversion efficiency. Another question, “What are likely to be your biggest business challenges in the next 5-10 years?” found the most frequent answer to be Net Zero (Carbon) and environmental impact, followed by loss of subsidies, then efficiency & profitability, staff recruitment, and finally equal frequency was found for the issues of challenges to red meat consumption, sustainability and the need for increased uptake of genetics technology. This suggests that genetics technologies are most likely to be used by industry stakeholders to address environmental issues and maximise profit, rather than maximising yield per se.
- Genetic technologies are particularly placed to enhance the resilience of productivity under future extreme events/climate change. Indeed, the identification by beef and sheep genetics industry stakeholders of resilience/longevity of productivity as the second most common answer to the question of “how else could genetic information help your business?”<sup>122</sup> attests to this

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<sup>118</sup> Royal Society, 2024. Is it safe to eat GM crops? Available at: <https://royalsociety.org/news-resources/projects/gm-plants/is-it-safe-to-eat-gm-crops/>

<sup>119</sup> NASEM, 2016. Genetically engineered crops experiences and prospects. Available at:

<https://nap.nationalacademies.org/catalog/23395/genetically-engineered-crops-experiences-and-prospects>

<sup>120</sup> Caradus, 2023. Intended and unintended consequences of genetically modified crops—myth, fact and/or manageable outcomes? Available at: <https://www.tandfonline.com/doi/pdf/10.1080/00288233.2022.2141273>

<sup>121</sup> AbacusBio, 2022. A vision for improving the UK sheep and beef sectors through breeding over the next 10 years. Available at: <https://ahdb.org.uk/scoping-study-delivering-a-vision-for-improving-the-beef-and-sheep-sectors-through-animal-breeding-over-the-next-ten-years>

<sup>122</sup> *Ibid*

## 3.6 Innovation Area 5: Circular economy

### 3.6.1 Overview of scope

For the purposes of this report, circular economy as an agri-food innovation has been narrowed down to focus on the implementation of on-farm business models that incorporate circular economy principles, technologies, and processes that can reduce food loss or waste on farm, and the extent to which this overall gain in system efficiency creates the potential for reduced land use. The increased uptake of circular on-farm practices to reduce waste are expected to lower generation of on-farm food waste, potentially resulting in a reduced requirement for land needed per unit of produce brought to market. Examples of causes of on-farm, pre-farm gate food losses (hereafter 'food loss') and circular economy agri-innovations that can mitigate it are presented in Table 3-6.<sup>123</sup>

Losses generated during on-farm production can be broadly categorised as 'practice-based' and 'market-based'. 'Practice-based' refers to direct loss generated during the operations of growing, harvesting and rearing, whereas 'market-based' losses are generated as a result of external market events that influence agricultural production.

**Table 3-6: Examples of causes of food loss and mitigation circular economy agri-innovations**

On-farm / pre-farm gate food and production losses	Circular economy agri-innovation examples
Crops lost to weeds, diseases or pests	Changes to disease and pest management strategies; changes to sowing times and rotations
Crops damaged by extreme weather events	Improved soil structure to increase water holding capacity or enable greater drainage
Crops damaged during harvesting (or lost before harvesting)	Investment in improved harvesting machinery; improved weed management strategies
Crops not harvested due to mismatches between demand and production, or not meeting aesthetic requirements	Greater collaboration with customers with stronger risk mitigation; behaviour change campaigns on consumer perception; policy

**Scope Restrictions:** Though circular economy principles and food waste reduction have potential for broad environmental benefits at all stages of the food supply chain<sup>124</sup>, it was agreed during the initial scoping phase of the project that this innovation specifically relates to reducing on-farm, pre-farm gate food losses, as opposed to food losses relating to post-farm gate transportation and storage, or food waste arising from consumers or in retail. The focus on food loss and waste is due to the clear logical link between this and demand for agricultural land; many other circular economy approaches in farming are focused on input efficiency which may bring both economic and environmental benefits but would not typically impact land use. On-farm food loss can occur at multiple stages in the growing cycle – for example, losses can occur due to pests or disease early in the production cycle before being ready to harvest, or when it is harvest-ready but not harvested for various reasons. The literature reviewed did not explicitly distinguish between these and therefore both are considered within this research, but the focus of measures and impacts reviewed perhaps skews to the latter.

<sup>123</sup> UK Food Systems Programme, 2023. *Understanding & evaluating on-farm loss and waste in the UK*. Available at: <https://ukfoodsystems.ukri.org/wp-content/uploads/2023/08/Understanding-Evaluating-On-farm-loss-and-waste-in-the-UK.pdf>

<sup>124</sup> Gillman et al., 2019. Does on-farm food loss prevent waste? Insights from California produce growers. Available at: <https://www.sciencedirect.com/science/article/abs/pii/S0921344919303039>

**Technology readiness and adaption to date:** The range of solutions that could contribute to reducing on-farm, pre-farm gate food loss are readily available, technologically mature and economically accessible, at TRL 9.<sup>125,126</sup> However the innovations appear to not be widespread on farms due to various societal and economic factors. The literature indicates that farmers do not appear to view on-farm, pre-farm gate food loss as a significant problem relative to other pressures, and that it is often generated as a result of farmers employing risk-averse strategies to meet fluctuating and unpredictable demands in the wider market, while coping with the inherent uncertainties and risks involved in production.<sup>127</sup>

## 3.6.2 Potential impact

### 3.6.2.1 How could the innovation potentially affect land use?

This innovation has the potential to cause **minor change** in agricultural production practices and land use if the uptake of on-farm circular economy agri-innovations increases, and results in more product reaching the market, with an associated reduction in the land area needed for the same volume of sold produce. Such innovations might include: improved crop protection and livestock health; improved harvesting and forecasting techniques; acceptance or redirection of a broader range of products that may fall outside of tight product specifications; better alignment of supply and demand etc.) increases, leading to a reduction in on-farm pre-farm gate food losses. The summarised impact of change in terms of magnitude, likelihood and speed is presented in Table 3-7.

### 3.6.2.2 What is the likely impact across different sectors?

The literature did not generally distinguish between food loss relating to arable crops or horticultural production, but most literature related to reducing food loss in arable and horticulture agriculture as opposed to livestock. At a global level, it is understood that livestock food losses occur to a smaller degree than for arable and horticulture commodities<sup>128</sup> (partly as most meat processing would occur off-farm and livestock lost to disease may not be classified as 'food' loss in the same manner as crops, depending on the stage at which mortalities have occurred).<sup>129</sup>

**Table 3-7: Expected impact of change from circular economy innovations**

Impact	Magnitude	Speed	Likely uptake	Confidence in potential for impact
Scale	Minor	Gradual	Likely	Medium

<sup>125</sup> EIP\_AGRI, 2020. *Reducing food loss on the farm*. Available at: <https://ec.europa.eu/eip/agriculture/en/publications/eip-agri-focus-group-reducing-food-loss-farm-final.html>

<sup>126</sup> WWF, 2023. *Hidden waste: the scale and impact of food waste in primary production*. Available at: <https://www.wwf.org.uk/our-reports/hidden-waste>

<sup>127</sup> Campbell, D. and Munden-Dixon, K. 2018. *On-farm food loss: farmer perspectives on food waste*. Available at: <https://open.clemson.edu/joe/vol56/iss3/23/>

<sup>128</sup> O'Connor et al., 2023. *A critical review of on-farm food loss and waste: future research and policy recommendations*. Available at: <https://www.cambridge.org/core/journals/renewable-agriculture-and-food-systems/article/critical-review-of-onfarm-food-loss-and-waste-future-research-and-policy-recommendations/127E05ACFA8CBB22D60A1AFB7194A732>

<sup>129</sup> Lipinski, 2020. *Why Does Animal-Based Food Loss and Waste Matter?* Available at: [https://ct.prod.gefft.io/c2NpZW5jZWRpcmlVjdF9jb250ZW50aG9zdGluZyxdXAsaHR0cHM6Ly9hY2FkZW1pYy5vdXAuY29tL0dlldE70ckNvbnRlbnQvR2V0UGRmQnlEb2k\\_ZG9pPTlwLjEwOTMlMmZhZiUyZnZmYWVwMzkmcmVzb3VvY2V0eXBIPtQmcGFyZW50UmVzb3VvY2VUeXBISWQ9Mw.KBfSe4Nd78aNLuf6EexBLxcfcokWqG0UzV\\_WRfZ\\_2o8](https://ct.prod.gefft.io/c2NpZW5jZWRpcmlVjdF9jb250ZW50aG9zdGluZyxdXAsaHR0cHM6Ly9hY2FkZW1pYy5vdXAuY29tL0dlldE70ckNvbnRlbnQvR2V0UGRmQnlEb2k_ZG9pPTlwLjEwOTMlMmZhZiUyZnZmYWVwMzkmcmVzb3VvY2V0eXBIPtQmcGFyZW50UmVzb3VvY2VUeXBISWQ9Mw.KBfSe4Nd78aNLuf6EexBLxcfcokWqG0UzV_WRfZ_2o8)

### 3.6.2.3 Potential magnitude

**Potential for change:** The evidence indicates that the magnitude of change in land use as a result of the implementation of circular economy innovations is expected to be **incremental**. This innovation is expected to manifest in small changes to existing practices rather than a transformation in production practices. This means that there is a 'ceiling' on the potential reduction in land use requirement<sup>130</sup>, as a slightly smaller land area would be required than what is currently used to produce the same yields, rather than a significant displacement of land use. It should also be noted that some food loss will always be inevitable regardless of the implementation of circular economy practices, and moreover on-farm food waste can vary massively from year to year (e.g., due to extreme weather events).

**Evidence availability:** The evidence available to quantify the likely magnitude of change is limited, exacerbated by the lack of reliable data on on-farm food waste.<sup>131</sup> Most of the literature focuses on the quantity of food that could be consumed if it was not lost, which is then converted into potential land use reduction. This does not consider whether a reduction in on-farm pre-farm gate food loss would lead to land displacement in practice, or instead whether farmers would continue using the same amount of land with a higher yield.

**Scope for quantification:** The only available figure specifically for the UK is that 960,000 hectares 'worth' of agricultural land is used to produce food that is lost on farms (and 1.6 million hectares abroad).<sup>132</sup> This is not split by sub-sector (arable, horticulture, livestock) though based on discussion above it can be speculated that the greatest potential may be in the former two.

However, it is important to note that this figure arises from research from organisations with agendas relating to this topic and therefore the benefits may have been overstated. Moreover, this represents the area that is used, not the area that could be reduced, and therefore it should be viewed as a maximum potential upper estimate. Recognising that some on-farm food loss is inevitable and that there are significant barriers to the implementation of this innovation, but that simultaneously technologies and solutions are recognised and available, applying a 50% weighting to this figure to quantify a **potential realistic 480,000 hectares reduction in agricultural land use** seems reasonable, which equates to a 2.7% reduction.

This broadly aligns with academic literature which suggests that at the *global* scale, a 50% reduction in food waste (all) would result in a projected 11% reduction in all agricultural land use by 2050 compared with a business-as-usual approach.<sup>133</sup> Using a broad assumption that in Europe approximately 30% of food loss occurs on-farm,<sup>134,135</sup> this equates to 3.3% reduction, which applied to the UK's agricultural land use is a **potential realistic 594,000 hectares reduction in agricultural land use**.

The range in results of potential realistic agricultural land use change due to implementation of circular economy innovations to on-farm pre-farm gate food loss to ~2045 is between 2.7% and 3.3%, or between 480,000 and 594,000 hectares.

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<sup>130</sup> O'Connor et al., 2023. *A critical review of on-farm food loss and waste: future research and policy recommendations*. Available at: <https://www.cambridge.org/core/journals/renewable-agriculture-and-food-systems/article/critical-review-of-onfarm-food-loss-and-waste-future-research-and-policy-recommendations/127E05ACFA8CBB22D60A1AFB7194A732>

<sup>131</sup> Campbell, D. and Munden-Dixon, K. 2018. On-farm food loss: farmer perspectives on food waste. Available at: <https://open.clemson.edu/joe/vol56/iss3/23/>

<sup>132</sup> WWF, 2023. *Hidden waste: the scale and impact of food waste in primary production*. Available at: <https://www.wwf.org.uk/our-reports/hidden-waste>

<sup>133</sup> Röss et al., 2017. *Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures*. Available at: <https://www.sciencedirect.com/science/article/pii/S0959378016306872#sec0025>

<sup>134</sup> Lipinski, 2020. *Why Does Animal-Based Food Loss and Waste Matter?* Available at: [https://ct.prod.gefft.io/c2NpZW5jZWRpcmlVjdF9jb250ZW50aG9zdGluZyxyvdXAsaHR0cHM6Ly9hY2FkZW1pYy5vdXAuY29tL0dlldEz0ckNvbnRlbnQvR2V0UGRmQnlEb2k\\_ZG9pPTlEwLjEwOTMlMmZhZiUyZnZmYWwEwMzkmcmVzb3VyY2V0eXBIPtQmcGFyZW50UmVzb3VyY2VUeXBISWQ9Mw.KBfSe4Nd78aNluf6EexBLxcfcokWqG0UzV\\_WRfZ\\_2o8](https://ct.prod.gefft.io/c2NpZW5jZWRpcmlVjdF9jb250ZW50aG9zdGluZyxyvdXAsaHR0cHM6Ly9hY2FkZW1pYy5vdXAuY29tL0dlldEz0ckNvbnRlbnQvR2V0UGRmQnlEb2k_ZG9pPTlEwLjEwOTMlMmZhZiUyZnZmYWwEwMzkmcmVzb3VyY2V0eXBIPtQmcGFyZW50UmVzb3VyY2VUeXBISWQ9Mw.KBfSe4Nd78aNluf6EexBLxcfcokWqG0UzV_WRfZ_2o8)

<sup>135</sup> WWF, 2022. *Hidden waste: the scale and impact of food waste in primary production*. Available at: <https://www.wwf.org.uk/our-reports/hidden-waste-roadmap>

### 3.6.2.4 Barriers

There are multiple barriers that would prevent or reduce this innovation from being adopted, and from the implementation of this innovation leading to the potential maximum change in agricultural land use, with financial barriers and barriers to uptake on farms particularly impactful. These include:

- Lack of ability of farmers to amend practices due to market conditions (e.g., unable to negotiate flexible contracts and therefore cannot afford to harvest surplus food; overproduction in order to mitigate contractual risks);<sup>136</sup>
- Specific requirements and specifications for produce might cause on-farm pre-farm food loss (e.g., wonky fruit being rejected; specific strains being required to increase efficiency for consumers which may result in more waste on-farms) which necessitate a holistic whole supply chain approach;<sup>137</sup>
- Farms can be penalised for failing to produce a certain amount of crops, and also need to be able to produce a threshold amount in order to remain viable as a business, which causes challenges when trying to streamline production;
- Natural causes like diseases, pests, livestock mortality and extreme weather cause inevitable on-farm pre-farm gate food loss and are extremely challenging to mitigate; moreover these may become more variable and more extreme as the impacts of climate change become stronger and more prevalent – trends which might be expected to increase loss and waste in the absence of other action;<sup>138</sup>
- Operational challenges such as time constraints in harvesting and labour shortages for harvesting can lead to on-farm pre-farm gate food loss;<sup>139</sup>
- On-farm pre-farm gate food loss receives significantly less attention in literature and government policy than consumer and retail food waste, and this lack of research has implications for understanding and proposing solutions for the problem;<sup>140</sup>
- The factors leading to the occurrence of on-farm pre-farm gate food loss are complex, and the solutions sit at the interface between (amongst others) technology, economics, sociology and behavioural science.<sup>141</sup> Resolution of the barriers therefore requires a coordinated policy response.

### 3.6.2.5 Potential speed

The evidence indicates that this innovation (and consequent projected impact of land use) is likely to occur at a **gradual** rate, mostly because both behaviour change on farms and changes to existing food system dynamics can often take time to embed, and this issue may not be prioritised relative to other

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<sup>136</sup> Read et al., 2020. *Assessing the environmental impacts of halving food loss and waste along the food supply chain*. Available at: <https://www.sciencedirect.com/science/article/pii/S0048969719362515#:~:text=4.3.&text=Most%20studies%20of%20FLW%20interventions.increase%20system%2Dwide%20environmental%20impact>.

<sup>137</sup> O'Connor, J. 2023. *A critical review of on-farm food loss and waste: future research and policy recommendations*. Available at: <https://www.cambridge.org/core/journals/renewable-agriculture-and-food-systems/article/critical-review-of-onfarm-food-loss-and-waste-future-research-and-policy-recommendations/127E05ACFA8CBB22D60A1AFB7194A732>

<sup>138</sup> WRAP, 2019. *Food waste in primary production*. Available at: <https://www.wrap.ngo/resources/report/food-waste-primary-production-uk>

<sup>139</sup> Campbell, D. and Munden-Dixon, K. 2018. *On-farm food loss: farmer perspectives on food waste*. Available at: <https://open.clemson.edu/joe/vol56/iss3/23/>

<sup>140</sup> Read et al., 2020. *Assessing the environmental impacts of halving food loss and waste along the food supply chain*. Available at: <https://www.sciencedirect.com/science/article/pii/S0048969719362515>

<sup>141</sup> European Innovation Partnership for Agricultural Productivity and Sustainability, 2021. *Reducing food loss on the farm*. Available at: [https://ec.europa.eu/eip/agriculture/sites/default/files/eip-agri\\_factsheet\\_food\\_loss\\_2021\\_en.pdf](https://ec.europa.eu/eip/agriculture/sites/default/files/eip-agri_factsheet_food_loss_2021_en.pdf)

challenges and opportunities faced by farmers. Moreover, there is a general lack of quantitative data on the scale of on-farm pre-farm gate food loss<sup>142</sup>, and a general lack of interest from farmers in the benefits of reducing it, hence more research is likely required before this innovation is widely implemented. It is therefore predicted that this innovation would be widely implemented by the **2030-2040s**, though any changes in land use would likely materialise over longer timescales. The innovations are well-understood and with appropriate policy mechanisms and funding support could be implemented sooner.

### 3.6.2.6 Likely uptake

Our interpretation from the evidence suggests that this innovation is **likely** to occur. The barriers to implementation are fairly well understood, and solutions to the barriers (e.g., improved data; support to farmers to change business models where the need to over-produce is minimised; education on customer preferences) are recognised and technologically feasible. The required changes would require increased recognition, research and funding for the scale of the problem and the implementation of solutions, but not to an unrealistic degree. It should also be noted that in order to be successful, this innovation would require change from a wide range of actors in addition to farmers, including wholesalers and distributors, retailers, and consumers.

### 3.6.2.7 Confidence in potential for impact

The evidence base on the extent of on-farm pre-farm gate food loss is mixed. There is some research that attempts to quantify the extent of it, but there appears to not be an academic consensus that reducing food loss will lead to some reduction in land use, nor any academic literature that quantifies the impact of reduction on land use. The literature relating to barriers and proposed solutions to on-farm food loss is more extensive, which has informed the categorisation relating to incremental magnitude and gradual speed of change. Therefore the confidence in the occurrence of the described impacts is **medium**.

## 3.6.3 Discussion

There are several discussion points on wider impacts and potential unintended consequences to note:

- The literature indicates that the opportunities for reducing agricultural land use are greater from reducing consumer and retail food waste (thereby reducing demand for agricultural products) than from focusing on reducing direct losses at the production stage.<sup>143,144,145</sup>
- The mitigation measures to reduce pressure on natural resources and agricultural land are not completely correlated to those which aim to reduce greenhouse gas emissions as the objective, and the differing objectives determine whether interventions should focus more on losses or on waste, as savings (both for land use and greenhouse gas emissions) vary between products.<sup>146</sup>

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<sup>142</sup> WRAP, 2019. *Food waste in primary production*. Available at: <https://www.wrap.ngo/resources/report/food-waste-primary-production-uk>

<sup>143</sup> Read et al., 2020. *Assessing the environmental impacts of halving food loss and waste along the food supply chain*. Available at: <https://www.sciencedirect.com/science/article/pii/S0048969719362515#:~:text=4.3.&text=Most%20studies%20of%20FLW%20interventions,increase%20system%2Dwide%20environmental%20impact>.

<sup>144</sup> Gillman et al., 2019. *Does on-farm food loss prevent waste? Insights from California produce growers*. Available at: <https://www.sciencedirect.com/science/article/abs/pii/S0921344919303039>

<sup>145</sup> Hegwood et al., 2023. *Rebound effects could offset more than half of avoided food loss and waste*. Available at: <https://www.nature.com/articles/s43016-023-00792-z>

<sup>146</sup> Cattaneo et al., 2021. *The environmental impact of reducing food loss and waste: A critical assessment*. Available at: <https://www.sciencedirect.com/science/article/pii/S0306919220300920>

## 3.7 Innovation Area 6: Regenerative agriculture

### 3.7.1 Overview of scope

Rather than a particular innovation, regenerative agriculture is an approach to agriculture that adapts to the local environment to achieve positive environmental and soil health outcomes. It is guided by five general principles: 1) minimise soil disturbance, (2) keep the soil covered year-round, (3) keep live plants and roots in the soil for as long as possible, (4) incorporate biodiversity, and (5) integrate animals e.g. grazing animals on cover crops; this leads to improved, more resilient soil health, provides carbon sequestration, and biodiversity and other ecosystem services.<sup>147</sup> However, individual farms may take up different principles to different degrees and using different practices, based on the specific agroecological and climatic context of their farm, the pre-existing farming system, the socioeconomic context, and the aspirations or preferences of the farmer or land manager.<sup>148</sup>

Key reasons for taking up regenerative practices on farms are improved long term crop yield stability and consistency between the years<sup>149</sup> through improved long-term environmental resilience (e.g. to pests and diseases).<sup>150</sup> One mechanism for this effect is the increase in soil organic matter that is expected to lead to crop yields with higher resilience to environmental stressors due to the improved physical structure of soil (although there is scarce evidence for this effect<sup>151</sup>) but also due to greater soil water holding capacity in organically managed soils (e.g. legume and manure-based systems<sup>152</sup>).

Other benefits of regenerative agriculture include lower farm-level input costs<sup>153</sup>, improved food quality (higher micronutrient concentration<sup>154</sup>) less susceptibility to pests/diseases, higher pollinator abundance, and improved farmer mental health.<sup>155</sup> <sup>156</sup> The potential lower dependence on nitrogen inputs can increase farm economic resilience to volatile input/fuel prices. Economic resilience can also be improved by the potential for diversification of food production and potentially higher value produce.<sup>157</sup>

**Technology readiness and adaption to date:** As regenerative agriculture is not a single technology, rather a set of approaches to farming, it does not fit into the TRL scale. However, it is currently implemented on a commercial scale in the UK, with findings from one survey of UK farmers implying that >30% of farmers implement some form of sustainable soil management that correspond to regenerative agriculture principles to different degrees, and 30% of farmers experimenting with sustainable soil

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<sup>147</sup> Khangura et al., 2023. Regenerative Agriculture—A Literature Review on the Practices and Mechanisms Used to Improve Soil Health. Available at: <https://www.mdpi.com/2071-1050/15/3/2338>

<sup>148</sup> Khangura et al., 2023. Regenerative Agriculture—A Literature Review on the Practices and Mechanisms Used to Improve Soil Health. Available at: <https://www.mdpi.com/2071-1050/15/3/2338>

<sup>149</sup> O'Donoghue et al., 2022. Regenerative Agriculture and Its Potential to Improve Farmscape Function. Available at: <https://www.mdpi.com/2071-1050/14/10/5815>

<sup>150</sup> Khangura et al., 2023. Regenerative Agriculture—A Literature Review on the Practices and Mechanisms Used to Improve Soil Health. Available at: <https://www.mdpi.com/2071-1050/15/3/2338>

<sup>151</sup> Giller et al., 2021. Regenerative Agriculture: An agronomic perspective. Available at: <https://journals.sagepub.com/doi/abs/10.1177/0030727021998063>

<sup>152</sup> Lotter et al., 2003. The performance of organic and conventional cropping systems in an extreme climate year. Available at: <https://www.cambridge.org/core/journals/american-journal-of-alternative-agriculture/article/abs/performance-of-organic-and-conventional-cropping-systems-in-an-extreme-climate-year/C58A4083CDC83AC79FE4304794641B26>

<sup>153</sup> Groundswellag.com, 2024. Groundswell Benchmarking Group. Available at: <https://groundswellag.com/groundswell-benchmarking/>

<sup>154</sup> Li et al., 2023. A new Rothamsted long-term field experiment for the twenty-first century: principles and practice. Available at: <https://link.springer.com/article/10.1007/s13593-023-00914-8>

<sup>155</sup> O'Donoghue et al., 2022. Regenerative Agriculture and Its Potential to Improve Farmscape Function. Available at: <https://www.mdpi.com/2071-1050/14/10/5815>

<sup>156</sup> Khangura et al., 2023. Regenerative Agriculture—A Literature Review on the Practices and Mechanisms Used to Improve Soil Health. Available at: <https://www.mdpi.com/2071-1050/15/3/2338>

<sup>157</sup> Savills, 2024. Can farmers afford to switch to regenerative farming? Available at: [https://www.savills.co.uk/research\\_articles/229130/362979-0](https://www.savills.co.uk/research_articles/229130/362979-0)

management practices.<sup>158</sup> This suggests there is sizeable minority of UK farmers that practice regenerative approaches and/or are interested in it. For the purposes of this review, we are considering increased uptake of regenerative practices, rather than the implementation of novel techniques.

## 3.7.2 Potential impact

### 3.7.2.1 How could the innovation potentially affect land use?

The adoption of regenerative agriculture by farmers can enhance natural capital and protect ecosystems and soils. In the short term, this may result in lower crop yields and higher up-front costs to transition and manage the farm<sup>159</sup>, and more risk to farm output. In the long term, farm outputs may become more resilient to environmental changes and become more economically secure due to more diversified food production, price premiums for their produce (although while first adopters may attract a price premium, it is unclear if this would hold for a wider transition), and potential sales of ecosystem services.<sup>160</sup> Yields may then recover to pre-uptake levels, but this is far from certain. Current understanding and observation from the industry to date is that yields remain lower than conventional farming after multiple years,<sup>161,162</sup> meaning that to maintain the same yields, more land area is likely to be needed. The summarised impact of change in terms of magnitude, likelihood and speed is presented in Table 3-8.

### 3.7.2.2 What is the likely impact across different sectors?

**Arable & horticulture:** More land may be needed depending on region/crop type because of lower yields compared to conventional agriculture<sup>163</sup>, although different implementations of regenerative agriculture may affect yield differentially. For example, the effect on yield when transitioning from full-inversion till to no or minimum till has been shown in several studies to result in positive yield impacts, however this depends on agroclimatic conditions, crop, and soil factors, and as a result there is also a body of evidence showing no effect on yields of no-till uptake.<sup>164,165</sup>

**Livestock:** The approach to livestock management in regenerative systems is understood to entail more rotational grazing with longer rest periods for individual fields, but higher stocking densities than conventional grazing approaches when fields are grazed<sup>166</sup>. Little evidence was found on the potential effects of this on overall livestock output compared to conventional pasture systems. One systematic review and meta-analysis of the effect of rotational grazing and multispecies herbal ley integration on animal daily live weight gain in temperate oceanic climates<sup>167</sup> found that longer rest periods were required to maintain livestock growth rates at higher stocking densities. This implies that the weight gain

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<sup>158</sup> Jaworski et al., 2023. Sustainable soil management in the United Kingdom: A survey of current practices and how they relate to the principles of regenerative agriculture. Available at: <https://bsssjournals.onlinelibrary.wiley.com/doi/pdf/10.1111/sum.12908>

<sup>159</sup> Savills, 2023. Is regenerative agriculture financially viable? Available at:

[https://www.savills.co.uk/research\\_articles/229130/348021-0](https://www.savills.co.uk/research_articles/229130/348021-0)

<sup>160</sup> Savills, 2024. Can farmers afford to switch to regenerative farming? Available at:

[https://www.savills.co.uk/research\\_articles/229130/362979-0](https://www.savills.co.uk/research_articles/229130/362979-0)

<sup>161</sup> Groundswellag.com, 2024. Groundswell Benchmarking Group. Available at: <https://groundswellag.com/groundswell-benchmarking/>

<sup>162</sup> Savills, 2024. Can farmers afford to switch to regenerative farming? Available at:

[https://www.savills.co.uk/research\\_articles/229130/362979-0](https://www.savills.co.uk/research_articles/229130/362979-0)

<sup>163</sup> FFCC, 2021. Farming for Change Charting a course that works for all. Available at: <https://ffcc.co.uk/publications/farming-for-change-charting-a-course-that-works-for-all>

<sup>164</sup> Khangura et al., 2023. Regenerative Agriculture—A Literature Review on the Practices and Mechanisms Used to Improve Soil Health. Available at: <https://www.mdpi.com/2071-1050/15/3/2338>

<sup>165</sup> Jordon et al., 2022a. Temperate Regenerative Agriculture practices increase soil carbon but not crop yield—a meta-analysis. Available at: <https://iopscience.iop.org/article/10.1088/1748-9326/ac8609>

<sup>166</sup> Jordon et al., 2022b. Rotational grazing and multispecies herbal leys increase productivity in temperate pastoral systems – A meta-analysis. Available at <https://doi.org/10.1016/j.agee.2022.108075>

<sup>167</sup> Jordon et al., 2022b. Rotational grazing and multispecies herbal leys increase productivity in temperate pastoral systems – A meta-analysis. Available at <https://doi.org/10.1016/j.agee.2022.108075>

benefits from rotational grazing may be offset by the higher stocking densities in regenerative systems. Another result from this study was that sheep growth rates increased with higher leaf nitrogen concentrations in herbal leys, implying that integration of herbal leys could further compensate for productivity losses due to higher stocking densities. The combination of these effects and their overall impact on animal productivity will depend on the specific management context (e.g. prior stocking density, species type). We found no literature attempting to systematically or quantitatively link these effects to land use change.

**Table 3-8: Expected impact of change from regenerative agriculture**

Impact	Magnitude	Speed	Likely uptake	Confidence in potential for impact
Scale	Insignificant / negative	Intermediate	Unlikely – Moderately Likely*	Low

\*We have departed from a single classification here as the evidence review indicates it is likely some features of regenerative agriculture will be adopted more widely than others. This is flagged in greater detail in the text.

### 3.7.2.3 Potential magnitude

**Potential for change:** The magnitude of change in land use due to the implementation of regenerative agriculture is expected to be **systemic**. However, as there is no ‘one-size-fits-all’ approach, the effect on land use will vary by local context and it is not clear what the aggregate of these local effects on UK land use will be. Regenerative agriculture is an alternative way of understanding farming and its interaction with natural capital, such that unconventional management techniques become possible. For example, conventional agriculture separates livestock and arable production, but regenerative approaches can combine both synergistically. One important change for farmers is the higher focus on optimising for net margin rather than yield. A regenerative farm is likely to produce less total quantity of food, but its market value could be higher and input costs lower.<sup>168,169</sup> Regenerative farming has the potential to deliver greater economic benefit and resilience to farmers and deliver value to society in terms of higher food quality and diversity at the expense of total quantity, as well as increasing ecosystem service provisioning, ultimately increasing agricultural resilience in the long-term. Regenerative agriculture also disrupts the conventional monocropping approach by integrating more plant diversity into farming systems.

**Evidence availability:** The evidence available to quantify the likely magnitude of change is limited. Our approach to estimating potential land use impacts on arable land has been to use estimates of percent change in crop yield associated with uptake of regenerative agriculture as a proxy for the increased amount of land that will be required for regenerative agriculture.<sup>170,171,172</sup> For livestock, such estimates were not found, and we were not able to infer the likely magnitude of change from the literature.

<sup>168</sup> Savills, 2024. Can farmers afford to switch to regenerative farming? Available at:

[https://www.savills.co.uk/research\\_articles/229130/362979-0](https://www.savills.co.uk/research_articles/229130/362979-0)

<sup>169</sup> Groundswellag.com, 2024. Groundswell Benchmarking Group. Available at: <https://groundswellag.com/groundswell-benchmarking/>

<sup>170</sup> FFCC, 2021. Farming for Change Charting a course that works for all. Available at: <https://ffcc.co.uk/publications/farming-for-change-charting-a-course-that-works-for-all>

<sup>171</sup> Savills, 2024. Can farmers afford to switch to regenerative farming? Available at:

[https://www.savills.co.uk/research\\_articles/229130/362979-0](https://www.savills.co.uk/research_articles/229130/362979-0)

<sup>172</sup> Groundswellag.com, 2024. Groundswell Benchmarking Group. Available at: <https://groundswellag.com/groundswell-benchmarking/>

There are multiple permutations of integration of regenerative agriculture principles, and many environmental variables that can interact with these to affect yield. We did not encounter any studies that provide a comprehensive predictive understanding of this, nor how this could affect land use. It is noted in the literature that there is limited quantitative evidence on the effects of adopting regenerative practices.<sup>173</sup>

**Scope for quantification:** The FFCC model estimates ~17-27% less cereal yield would be achieved with regenerative agriculture compared to conventional agriculture. Savills (2024) assumed yields reduce by 26% at the start of a transition to regenerative agriculture, with some recovery to 18% below conventional farming by year 6. In agreement with this, data from the Groundswell Benchmarking Group indicates yields are 25% lower on average. We assume regenerative agriculture would require a proportional increase in land area to maintain food production following the reduction in yields. Assuming a range of 17-27% for all arable land, this translates into a range of ~700,000-1.1 million additional hectares that would be needed. However, it is important to note that the magnitude of yield reductions and its potential effect on land use will likely depend on the extent to which regenerative practices are adopted by farmers. Farmers that implement a small number of practices or focus on a single regenerative principle may see much lower or no yield reductions or potentially positive yield effects (e.g. consider the literature on the adoption of no or minimum till practices<sup>174 175</sup>), compared to farmers that holistically transform their approach to align with a greater number of regenerative principles. Further, regenerative agriculture adoption must be considered in the context of improving yield resilience to future climate change effects, which is not taken into account with a like-for-like comparison of regenerative agriculture yields with present-day conventional farming yields (see Section 3.7.3 for further discussion on this point).

### 3.7.2.4 Barriers

One survey of 297 UK farmers by Jaworski et al. (2023) on their perspectives on regenerative agriculture practices found multiple reported barriers that prevent further uptake.<sup>176</sup> These most frequently reported barriers included:

- capital costs of seeds, equipment and infrastructure (24% of respondents);
- weather, climate and climate change (increased variability of weather) (15%);
- profitability due to yield variability and increased costs (14%);
- logistics (animal health, labour, access to alternative inputs) (12%);
- access to unbiased, concise and locally adapted knowledge (11%);
- time constraints (implementing and trialling new practices under favourable weather) (10%).

Other barriers identified by farmers in the Jaworski et al. (2023) survey were soil limitations (soil type, topography and soil problems), lack of research measuring/quantifying the benefits of sustainable soil management practices, lack of governmental incentives, restrictions from regulations and certification schemes. Since there is no one definition of regenerative agriculture, it is likely to depend on the local context which complicates certification and standardisation.

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<sup>173</sup> Berthon et al., 2024. Measuring the transition to regenerative agriculture in the UK with a co-designed experiment: design, methods and expected outcomes. Available at: <https://iopscience.iop.org/article/10.1088/2976-601X/ad7bbe/meta>

<sup>174</sup> Khangura et al., 2023. Regenerative Agriculture—A Literature Review on the Practices and Mechanisms Used to Improve Soil Health. Available at: <https://www.mdpi.com/2071-1050/15/3/2338>

<sup>175</sup> Jordon et al., 2022a. Temperate Regenerative Agriculture practices increase soil carbon but not crop yield—a meta-analysis. Available at: <https://iopscience.iop.org/article/10.1088/1748-9326/ac8609>

<sup>176</sup> Jaworski et al., 2023. Sustainable soil management in the United Kingdom: A survey of current practices and how they relate to the principles of regenerative agriculture. Available at: <https://bsssjournals.onlinelibrary.wiley.com/doi/pdf/10.1111/sum.12908>

### 3.7.2.5 Potential speed

The same survey by Jaworski et al. (2023) found that the majority of farmers surveyed are strongly concerned about soil degradation, over 60% are aware of regenerative agriculture practices, and >30% of were implementing sustainable soil management methods. Techniques most often experimented with in mixed arable systems were cover crops, no till or minimum till, non-chemical fertilisers, increasing crop diversity, and holistic grazing. Sustainable soil management in the UK is driven by accreditation and certification schemes, facilitated groups including public, private, formal and informal, farmer networks, championing experts and farmers, online platforms<sup>177</sup>, suggesting a diverse range of infrastructure available to support with regenerative agriculture uptake. The majority of farmers taking part in the survey were members of one or more formal networks. The survey also suggested that younger farmers may be more amenable to uptake of regenerative approaches and that a paradigm shift could occur with the younger generations replacing older ones, although this will likely depend on how comparable the returns are compared to traditional approaches to farming, which is itself likely to depend on the local context of a given farm. Additionally, other important factors that will shape uptake going forward are government policies and the extent to which they create a favourable incentive landscape for farmers, and demand factors like retailer specifications for produce. How these factors will influence uptake is not clear. These findings suggests that regenerative agriculture is already happening to different degrees in the UK and more widespread and comprehensive implementation could develop in the **2020-2030s**.

### 3.7.2.6 Likely uptake

Our assessment of the available evidence is that this innovation is **unlikely** to occur equally in all dimensions. Different practices have different barriers to entry and implications for farm output, depending on the local farming context as well. However, the number of farms holistically transforming to regenerative agriculture may be relatively small, without significant policy or demand side pushes, given that in isolation it may have somewhat negative short-term effects on yield and require a comprehensive transition of farm management approaches. In contrast, some specific elements (such as cover cropping) may become widespread even with minimal policy or demand-side pushes. There is uncertainty about all the potential drivers for change, including, the extent to which incentives like government policy, retailer specifications, consumer demand, and potentially improved resilience of farming to the impacts of climate change may shape uptake in future. See the below sections for the evidence underpinning this and other ratings for regenerative agriculture.

The barriers to uptake can be overcome with proper incentives, education and further research. The research by Savills (2024) notes that there are financial incentives through the improved SFI payment rates since 2023 for supporting the transition to regenerative agriculture in England, while Scotland and Wales will support regenerative principles through government schemes from 2026-2027. The scientific research is evolving as well, with more rigorous and comprehensive studies and methodologies developing to measure the outcomes of regenerative agriculture adoption for soil health, biodiversity, yield, grain health, and social and political change in a holistic way that is sensitive to the local context of implemented changes.<sup>178</sup> This can facilitate addressing knowledge gaps and limited evidence that may hinder wider adoption.

### 3.7.2.7 Confidence in potential for impact

We have a **low** confidence in the evidence base for this innovation. It is inherently difficult to estimate effects of regenerative agriculture on land use change due to the context-specificity of its effects, as

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<sup>177</sup> Jaworski et al., 2023. Sustainable soil management in the United Kingdom: A survey of current practices and how they relate to the principles of regenerative agriculture. Available at: <https://bsssjournals.onlinelibrary.wiley.com/doi/pdf/10.1111/sum.12908>

<sup>178</sup> Berthon et al., 2024. Measuring the transition to regenerative agriculture in the UK with a co-designed experiment: design, methods and expected outcomes. Available at: <https://iopscience.iop.org/article/10.1088/2976-601X/ad7bbe/meta>

well as the wide range of regenerative agriculture approaches a given farmer may decide to take up. Additionally, we found no empirical data in the literature that attempted to quantify land use effects of regenerative agriculture uptake.

### 3.7.3 Discussion

There are some discussion points on wider impacts and potential unintended consequences to note:

- Widespread adoption of regenerative agriculture with lower yields may necessitate an increase in the area of farmland to maintain constant domestic production levels. Regenerative agriculture may offer efficiencies from mixed livestock and arable farming e.g. using existing cropland as overlapping area with livestock to account for spillover, but we found no literature exploring such a scenario. It seems more likely that widespread regenerative agriculture adoption will occur on a fixed total agricultural land area, resulting in reduced domestic food production. Assuming no synergies with other innovations, more food imports will then be needed to maintain the existing food supply, potentially offshoring land use impacts of agriculture to other countries.
- A key rationale for regenerative agriculture is increasing resilience. One econometric model of weather effects on global agricultural productivity estimated that climate change has lowered agricultural yields.<sup>179</sup> Transitioning to regenerative practices can be seen as a form of mitigation against future occurrence of this effect, such that on balance, the future yield accounting of regenerative farming may be favourable compared to the status quo. This also adds nuance to the potential for regenerative farming to drive up food prices and make nutritious food less accessible to the average consumer, as the counterfactual under conventional farming may also see increased and more volatile food prices over time with lower supply and more susceptibility to extremes.

## 3.8 Interactions between the innovations

The findings from this research support one of the findings from the Vivid Economics report that “given the varied needs of the food system, the interdependencies of innovations, and the diversity of future outcomes, a single innovation is unlikely to represent a silver bullet indicating support for a diverse portfolio of agri-food innovations.” The net impact of innovation (primarily in terms of potential magnitude) is likely to be greatest when optimised with contributions from multiple changes. However, it is also the case that there may be some overlap in assumed impacts (e.g. a benefit of vertical farming is intended to be reduced food loss and waste).

The evidence reviewed did not support a detailed analysis of likely interactions within the scope of this project. Detailed consideration (and quantification) of these dependencies will link to ongoing research and modelling being undertaken by the LUNZ Hub. However, the research team would suggest that interactions can be thought of in three broad categories. Table 3-9 maps how the innovations interact with each other, using three categories: **positive reinforcement** (where innovations enhance each other's effectiveness), **headwinds** (where innovations may conflict and reduce each other's impact), and **neutral** (where innovations operate independently with no significant effect on each other) as broad trends projected through to 2050.

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<sup>179</sup> Ortiz-Bobea et al., 2021. Anthropogenic climate change has slowed global agricultural productivity growth. Available at: <https://www.nature.com/articles/s41558-021-01000-1#citeas>

**Table 3-9. A qualitative assessment of potential interactions and synergies between assessed agricultural innovations in terms of impacting agricultural land use**

Note: this table considers direct interactions. We debated using the term 'headwinds' to indicate where the impacts of the innovations may be offset or reduced when the innovations are applied together, compared to when applied individually. We decided against this as the innovations are not directly opposed; therefore the term 'neutral' is used. However, it should be noted that the innovations may not lead to additive or cumulative impacts when applied together as one innovation may reduce the scope for impact of another. Moreover, where an interaction is 'neutral', it should be noted that these innovations may still affect each other indirectly through market mechanisms or knowledge sharing.

All interactions are proposed with low levels of confidence given the limited scope of this study. To avoid duplication of text, cells are greyed out where the interaction of two innovations has already been discussed.

Innovation	Vertical agriculture	Precision agriculture	Genetic technologies	Circular economy
<b>Protein transition</b>	<b>Neutral</b> (no animal agriculture impact expected)	<b>Neutral</b> (this study focused on inputs and practices for arable and horticulture)	<b>Neutral</b> (minimal evidence was found, and lead in times for genetic changes in livestock may be long, but cannot logically be ruled out)	<b>Uncertain</b>
<b>Vertical agriculture</b>		<b>Neutral</b> (it is assumed that the benefits of precision agriculture are already factored in to estimates of vertical agriculture gains)	<b>Positive reinforcement</b> (could mitigate any risks relating to disease and crop resistance)	<b>Neutral</b> (it is assumed that high levels of efficiency and minimal waste are already factored in to estimates of vertical agriculture potential)
<b>Precision agriculture</b>			<b>Neutral</b> (it is assumed that the benefits of genetic technologies may already be factored in for precision agriculture models though synergies are possible)	<b>Uncertain</b>
<b>Genetic technologies</b>				<b>Uncertain</b>

**Regenerative agriculture** does not fit neatly into the categorisation used for other innovations. At least in the short term the research suggested that regenerative agriculture will need more land than conventional agriculture for the same levels and types of production (though the scale of difference is uncertain). However, if deployed alongside the other innovations in this study, this impact could be reduced or eliminated, enabling a transition to regenerative agriculture at the same time as reductions in overall land use.

Although included in the tabular comparison, **circular economy** interactions were hard to assess. In some cases food waste and loss improvements are likely to already be assumed by the interacting technology (e.g. vertical agriculture typically suggests reduced losses as a direct benefit). In other cases the interaction may be complex (e.g. a widespread protein transition might impact cases where organic material streams are directed as feeds and require assumptions to be made about relative levels of waste in different productive sectors) and is out of scope of the current study.

## 4.0 Conclusions

A summary of the expected scale of impact of the six in-scope agri-innovations across the axes of impact is provided in Table 4-1 (overleaf), and the main concluding remarks are as follows:

- **The benefits of these innovations may not always or primarily manifest in reduced land use.** Though all the innovations are expected to lead to general environmental benefits, this may manifest more strongly in reducing system inputs or reducing greenhouse gas emissions as opposed to significant change in agricultural land requirements in the UK.
- **Similarly, increased productivity or increased yields may not ultimately lead to actual land use savings.** There was little available literature that linked increased productivity of land directly to reduced land use, as opposed to farms continuing to use the same quantity of land with higher margins or profitability.
- **Impacts on land use abroad may be more significant.** This is most notable when considering the impacts of the protein transition; in terms of the magnitude of land used for cultivating animal feed domestically compared to abroad, land displacement is likely to occur from the UK's land footprint overseas. This is a positive when the footprint reduces – but could be a negative if it increases (for example if there is a change in UK production that is not reflected in UK consumption and thus increases imports).
- **The analysis of the predicted magnitude, especially any quantification of magnitude, is highly uncertain.** The majority of the data on the land use impacts of these innovations are theoretical and sourced from literature that is inevitably grounded in limited information from small-scale trials. Therefore estimates should be taken as indicative rather than as projections.
- **A combination of innovations may have greater impact than the 'sum of its parts'.** It is challenging to state which innovation may be the most impactful in terms of affecting land use, and it is likely than a mix of innovations would produce optimum impacts – even among those innovations that are likely to be adopted, synergies, dependencies, and the scope to offset downside risk are significant (for example, compensating for any downside risks to yields for regenerative agriculture). Conversely, some high-end estimates of potential benefit may overlap. For example, if land use due to livestock agriculture decreases as a result of a shift in protein production, it is not analytically appropriate to *also* assume reductions in food waste leading to land use savings for elements of production that would no longer be required.
- **The implementation of these innovations is dependent on consistent policy incentives.** Barriers to each innovation included numerous non-technical barriers which could be significant in affecting the uptake and consequent impacts, including the need for a longer-term, predictable policy environment, and greater focus on increasing dissemination of existing knowledge to encourage uptake.
- **Economic benefits are the driving factor of implementation.** The economic and operational feasibility of the innovations are key to adoption by farmers; social and especially economic constraints on how these innovations can be rolled out in an economically feasible way at scale is a more likely and significant constraint than technological readiness. These constraints are not necessarily well reflected in the literature which appeared to mostly focus on technical feasibility alone. Similarly, the innovations are not usually implemented because of their impact on land use; land use is happening as a by-product, with perceived economic benefit the main driving factor.

**Table 4-1: Summary of expected impact of each innovation on agricultural land use in terms of magnitude (qualitative and quantitative), speed, likely uptake and confidence in potential for impact.**

Please note that the 'description' of each innovation outlines how the innovation may be expected to lead to reduced land use rather than a projection of what will happen in practice. Also, as throughout the report, note that all land use change should be considered as **potential** due to the technical and socio-economic barriers described above, and the **uncertainty** relating to the causal link between increased productivity and reduced land use. The quantified land use change figures represent a potential trajectory that considers the feasible technical development but simultaneously incorporates the impact of the identified barriers on likely land use change. Again, as outlined throughout this report, quantification is limited as most estimates are based on academic studies and small-scale trials without adequately accounting for the challenges and realities of large-scale implementation.

Theme	Description	Magnitude	Range in estimates of potential land use change	Speed	Likely uptake	Confidence in potential for impact
<b>Protein transition</b>	Increased availability of plant-based / non-meat alternatives (for human consumption) and innovative animal feeds displace conventional products and reduce land use required for rearing and feed production.	<b>Significant</b> (though not transformative). The technical potential of alternative proteins is immense but price barriers and behavioural change interventions (amongst other barriers) means this is unlikely.	Shifts in animal feed could potentially free up 1 million hectares, though there is uncertainty about domestic versus international impacts even so. Changes due to human consumption are highly uncertain, with the high end estimate of 9 million hectares dependent on significant shifts in demand; current trends would deliver much smaller savings.	<b>Gradual</b> , in the range of 2030-2040 for cultural meats and 2040-2050 for more innovative products and alternative animal feedstocks. This is because consumer behavioural change takes a long time to implement and depends on whether the decisions to amend protein sources is cost-effective for producers.	<b>Moderately.</b> Alternative proteins are available so technological barriers are not the primary limiting factor; instead this is acceptance of alternative proteins from a behavioural and financial perspective.	<b>Low.</b> Though there is a general consensus that some form of protein transition will occur, there does not appear to be consensus whether this will be to a sufficiently significant degree to impact land use.
<b>Vertical agriculture</b>	Food is produced in controlled-environment multi-storey warehouses such that food yield	<b>Minor.</b> For the foreseeable future, this innovation is economically feasible only for a	Less than 70,000 hectares	<b>Intermediate</b> for horticultural growing. Growth of the market is expected to range between	<b>Moderately.</b> Vertically farmed produce is already commercially successful in the UK	<b>Medium.</b> There is wide agreement on the theoretical potential for vertical farming to disrupt

Theme	Description	Magnitude	Range in estimates of potential land use change	Speed	Likely uptake	Confidence in potential for impact
	increases by a factor proportional to the number of additional floors. The amount of food produced per unit of land is multiple times higher than conventional farming thereby reducing the need for agricultural land to maintain the same food output.	limited range of high-value horticultural crops, so there is a ceiling on the reduction in agricultural land use that vertical agriculture could lead to.		~24-28% CAGR. Given that 30% of UK basil sold in supermarkets is currently produced via vertical farming, a CAGR of 24% (assuming this approximates production growth) implies that horticultural production in vertical farms could supply 100% of the UK produce of ~7-8 different horticultural crops in the 2030-2040s.	and is projected to continue growing as an industry in the coming years. However, capital costs appear likely to be a persistent challenge due to the need to secure appropriate real estate and high-tech equipment and expertise. Energy requirements have much potential for efficiency gains, however, the fundamental physical constraints of indoor growing impose high energy demand compared to conventional growing in perpetuity.	conventional food production. However, we found no studies for horticulture that directly attempt to quantify its feasibility considering the practical barriers to implementation, and no studies quantifying its impact on land use.
<b>Precision agriculture technologies</b>	Uptake of precision agriculture technologies like machine guidance and variable rate nitrogen application can lead to higher food output on the same area of land, e.g. through	<b>Minor.</b> Given the existing relatively high integration of precision agriculture technologies in UK farming, further uptake is unlikely to have substantial effects on yield, especially since our	Between 170,000-339,000 hectares	<b>Rapid.</b> Precision agriculture technology is already widespread in UK agriculture, with rapid uptake having occurred in previous decades. The science on how to improve these	<b>Likely.</b> Barriers to implementation do not appear to impose fundamental limits on uptake. PAT uptake has a strong historical precedent in the UK.	<b>Medium.</b> Historical trends in crop yields provide an indication of the potential effect on crop yield over time as PAT has been taken up. However, there is a low amount of

Theme	Description	Magnitude	Range in estimates of potential land use change	Speed	Likely uptake	Confidence in potential for impact
	reducing unutilised land on-farm, optimising planting distances, and alleviating temporal mismatches between when plants need nutrients the most and when they are available.	understanding is the technologies are used primarily to reduce inputs rather than increase yields given the same inputs. These technologies cause changes to agricultural production through a series of step-changes at the individual field level over time as technologies improve (noting that there will certainly be physiological limits to gains that can accrue).		technologies is advancing in a large and increasing body of literature.		academic literature providing data on the changes in crop yields with adoption of PAT technologies in a UK context.
<b>Genetic technologies</b>	Genetic technologies (e.g., gene editing) create new strains with favourable genetic traits or eliminating unfavourable genes that hamper productivity or health, leading to increased food yield per plant or animal given equivalent inputs, leading to a	<b>Significant.</b> Crop and livestock production is likely to benefit from continuous genetic interventions over time. Double-digit percentage increases in yield have been observed over past decades in livestock and crop production as a consequence of less	Between 214,000-1.28 million hectares (arable only)	<b>Intermediate.</b> Double-digit percent gains in yields have occurred over multiple decades e.g. for GMO, gains have occurred over two decades. The uptake of gene editing could technically happen within the next decade, accruing yield benefits within	<b>Likely.</b> There is a strong historical precedent for uptake of genetic technologies given the commercial success of GMO worldwide over the past 2 to 3 decades as well as the long history of selective breeding in agriculture, suggesting that	<b>Medium.</b> While multiple sources point towards genetic technologies causing meaningful increases in agricultural yields, we found no direct evidence for horticultural crops or livestock yield gains other than for dairy. Some evidence was

Theme	Description	Magnitude	Range in estimates of potential land use change	Speed	Likely uptake	Confidence in potential for impact
	lower number of plants / animals needed for same total production	sophisticated genetic techniques than are available today.		the 2030-2040s decades.	public perception barriers can be readily overcome. Given that gene editing already exists as a mature technology, the regulatory reform occurring with the Precision Breeding Act in 2023 has provided an avenue for widespread implementation of gene editing in UK markets.	not UK specific, limiting the applicability of the findings.
<b>Circular economy</b>	The implementation of on-farm business models that incorporate circular economy principles, technologies, and processes that can reduce food loss or waste on farm reduces the generation of on-farm food waste, resulting in a reduced requirement for land needed per unit of produce.	<b>Minor.</b> The innovation could manifest in small changes to existing practices rather than transform production practices, hence there is a ceiling on the reduction in land use that circular economy innovations could lead to.	Between 480,000 and 600,000 hectares	<b>Gradual</b> , in the 2030-2040s, as on-farm behavioural changes and changes to existing food system dynamics can take a long time to change, barriers relating to resistance by producers would need to be overcome, and the measures would need to be cost-effective for farmers to implement.	<b>Likely.</b> Solutions to barriers are readily available and the benefits to farmers in terms of cost savings are relatively well-understood.	<b>Medium.</b> There is little academic literature relating to on-farm food waste and its impact on land use, and it may be that reduced waste simply improves yields with no change in land use.

Theme	Description	Magnitude	Range in estimates of potential land use change	Speed	Likely uptake	Confidence in potential for impact
<b>Regenerative agriculture</b>	An approach to agriculture that adapts to the local environment to achieve positive environmental and soil health outcomes, guided by five general principles: 1) minimise soil disturbance, (2) keep the soil covered year-round, (3) keep live plants and roots in the soil for as long as possible, (4) incorporate biodiversity, and (5) integrate animals e.g. grazing animals on cover crops; In the short term, this may result in lower crop yields, such that a larger area of land is required to maintain the same food output.	<b>Insignificant / negative.</b> It is estimated that regenerative agriculture causes a yield reduction of between 17-27% compared to conventional arable farming.	Between -700,000 to -1.1 million hectares (arable only)	<b>Intermediate.</b> Regenerative practices are already widespread in UK agriculture and there is a growing interest in it especially amongst younger farmers. However, transitioning a farm to regenerative practices can take multiple years and there are various cost and management barriers that can slow uptake. We estimate that more widespread and comprehensive implementation could develop in the 2020-2030s.	<b>Unlikely – Moderately Likely.</b> Some aspects of regenerative practice may become widely normalised, but it is unlikely all regenerative practices will be adopted on large numbers of farms unless there are significant regulatory or demand-side factors prompting this. Without these, the potential for small losses in productivity in the short term, and the fact that while first movers may enjoy a price premium, this may not be realisable for the mass market without wider market changes, mean widespread adoption is less likely.	<b>Low.</b> It is inherently difficult to estimate effects of regenerative agriculture on land use change due to the context-specificity of its effects, as well as the wide range of regenerative agriculture approaches a given farmer may decide to take up. Additionally, we found no empirical data in the literature that attempted to quantify its land use effects.

# Appendix

# A.1.0 References

- AbacusBio (2023) *Scoping study: Delivering a vision for improving the beef and sheep sectors through animal breeding over the next 10 years*. Available at: <https://ahdb.org.uk/scoping-study-delivering-a-vision-for-improving-the-beef-and-sheep-sectors-through-animal-breeding-over-the-next-ten-years>
- Agritecture & WayBeyond (2021) *Global CEA Census Report*. Available at: <https://engage.farmroad.io/hubfs/2021%20Global%20CEA%20Census%20Report.pdf>
- Actual Market Research (AMR) (2022) *United Kingdom Vertical Farming Market Research Report, 2027*. Available at: <https://www.actualmarketresearch.com/product/uk-vertical-farming-market>
- Asseng, S., Guarin, J.R., Raman, M., Monje, O., Kiss, G., Despommier, D.D., Meggers, F.M. & Gauthier, P.P.G. (2020) *Wheat yield potential in controlled-environment vertical farms*. *Proceedings of the National Academy of Sciences U.S.A.*, 117 (32) 19131-19135.
- Benke, K., & Tomkins, B. (2017). *Future food-production systems: vertical farming and controlled-environment agriculture*. *Sustainability: Science, Practice and Policy*, 13(1), 13–26.
- Berthon, K., Jaworski, C.C., Beacham, J.D., Jackson, P., Leake, J., McHugh, N.M., Capstick, L., Daniell, T., Krzywoszynska, A., Cameron, D., Holland, J., Hartley, S., Desneux, N., Jowett, K., Zhao, Y., Watt P.J. & Dicks, L.V. (2024) *Measuring the transition to regenerative agriculture in the UK with a co-designed experiment: design, methods and expected outcomes*. *Environmental Research: Food Systems*, 1, 025007.
- Bier, E. (2021) *Gene drives gaining speed*. *Nature Reviews Genetics*, 23, 5–22.
- Bradshaw, S. & Wentworth, J. (2023) *Future of Horticulture*. UK Parliament Post.
- Brito, L.F., Bedere, N., Douhard, F., Oliveira, H.R., Arnal, M., Peñagaricano, F., Schinckel, A.P., Baes, C.F. & Miglior, F. (2021) *Review: Genetic selection of high-yielding dairy cattle toward sustainable farming systems in a rapidly changing world*. *Animal*, 15:1, 100292.
- Burton, R.J.F. (2019) *The potential impact of synthetic animal protein on livestock production: The new "war against agriculture"?*. *Journal of Rural Studies*, 68, 33-45.
- Campbell, D. and Munden-Dixon, K. *On-Farm Food Loss: Farmer Perspectives on Food Waste*. *The Journal of Extension*, 56(3), Article 23.
- Caradus, J.R. (2023) *Intended and unintended consequences of genetically modified crops – myth, fact and/or manageable outcomes?* *New Zealand Journal of Agricultural Research*, 66:6, 519-619
- Cattaneo, A., Federighi, G. & Vaz, S. (2021) *The environmental impact of reducing food loss and waste: A critical assessment*. *Food Policy*, 98, 101890.
- Cattaneo, A., Sánchez, M.V., Torero, M. & Vos, R. (2021) *Reducing food loss and waste: Five challenges for policy and research*. *Food Policy*, 98, 101974.
- Clapp, J. & Ruder, S.-L. (2020) *Precision Technologies for Agriculture: Digital Farming, Gene-Edited Crops, and the Politics of Sustainability*. *Global Environmental Politics*, 20(3): 49–69.
- Collas, L. & Benton, D. (2024) *A new land dividend: the opportunity of alternative proteins in Europe*. Green Alliance.
- Collet, K., O'Callaghan, B., Mason, M., Godfray, C. & Hepburn, C. (2021) *The climate impact of alternative proteins*. Oxford Smith School of Enterprise and the Environment.

Department for Environment, Food & Rural Affairs (DEFRA) (2013) *Farm practices survey October 2012 - current farming issues*. Available at: <https://www.gov.uk/government/statistics/farm-practices-survey-october-2012-current-farming-issues>

Department for Environment, Food & Rural Affairs (DEFRA) (2022) *Agricultural land use in the United Kingdom*. Available at: <https://www.gov.uk/government/statistics/agricultural-land-use-in-the-united-kingdom>

Dhugga, K.S. (2022) *Gene Editing to Accelerate Crop Breeding*. *Frontiers in Plant Science*, 13:889995.

Duluins, O. & Baret, P. (2024) *A systematic review of the definitions, narratives and paths forwards for a protein transition in high-income countries*. *Nature Food* 5, 28-36.

European Commission (2021) *EIP-AGRI Focus Group Reducing food loss on the farm: Final report*. Available at: <https://ec.europa.eu/eip/agriculture/en/publications/eip-agri-focus-group-reducing-food-loss-farm-final.html>

Food, Farming & Countryside Commission (FFCC) (2021) *Farming for Change: Charting a course that works for all*. Available at: <https://ffcc.co.uk/publications/farming-for-change-charting-a-course-that-works-for-all>

Fortune Business Insights (FBI) (2024) *Vertical Farming Market Size, Share & Industry Analysis, By Type (Hydroponics, Aeroponics, and Aquaponics), By Structure (Building-Based Vertical Farms and Shipping-Container Vertical Farms), By Component (Lighting System, Irrigation and Fertigation System, Climate Control, Sensors, and Others), and Regional Forecast, 2024-2032*. Available at: <https://www.fortunebusinessinsights.com/industry-reports/vertical-farming-market-101958>

Freund, F., Soisontes, S., Laquai, V. & Banse, M. (2025) *Global land-use implications of preference shifts towards regional feed and sustainable diets in Germany and the European Union*. *Ecological Economics*, 228, 108455.

Frontier Agriculture (2024) *Variable Rate Nitrogen*. Available at: <https://www.soyl.com/services/variable-rate-nitrogen>

Frontier Economics (2023) *Delivering Insect-Based Feed at Scale*. Available at: <https://www.frontier-economics.com/media/012jxgjt/frontier-economics-delivering-insect-feed-at-scale-final-report-01-12-23.pdf>

Giller, K.E., Hijbeek, R., Andersson, J.A., & Sumberg, J. (2021). *Regenerative Agriculture: An agronomic perspective*. *Outlook on Agriculture*, 50(1), 13-25.

Hall, S.J.G. (2018) *A novel agroecosystem: Beef production in abandoned farmland as a multifunctional alternative to rewilding*. *Agricultural Systems*, 167, 10-16.

Hegwood, M., Burgess, M.G., Costigliolo, E.M., Smith, P., Bajželj, B., Saunders, H. & Davis, S.J. (2023) *Rebound effects could offset more than half of avoided food loss and waste*. *Nature Food* 4, 585-595.

Infarm (2022) *Infarm successfully demonstrates the tremendous potential of indoor-grown wheat*. Available at: <https://www.infarm.com/news/Infarm-demonstrates-potential-of-indoor-grown-wheat>

Jaworski, C.C., Krzywoszynska, A., Leake, J.R. & Dicks, L.V. (2023) *Sustainable soil management in the United Kingdom: A survey of current practices and how they relate to the principles of regenerative agriculture*. *Soil Use and Management*, 40, e12908.

Jones, E. (2022) *Enhancing farm efficiency with variable rate nitrogen – What do the latest trials results tell us?*. *Frontier Agriculture*. Available at: <https://www.frontierag.co.uk/blog/enhancing-farm-efficiency-with-variable-rate-nitrogen-what-do-the-latest-trials-results-tell-us>

Jordon, M.W., Willis, K.J., Bürkner, P.J., Haddaway, N.R., Smith, P. & Petrokofsky, G. (2022) *Temperate Regenerative Agriculture practices increase soil carbon but not crop yield—a meta-analysis*. *Environmental Research Letters*, 17(9).

Kaiser, E., Kusuma, P., Violet-Chabrand, S., Folta, K., Liu, Y., Poorter, H., Woning, N., Shrestha, S., Ciarreta, A., van Brenk, J., Karpe, M., Ji, Y., David, S., Zepeda, C., Zhu, X.-G., Huntenburg, K., Verdonk, J. C., Woltering, E., Gauthier, P. P. G., Courbier, S., Taylor, G. & Marcelis, L. F. M. (2024) *Vertical farming goes dynamic: optimizing resource use efficiency, product quality, and energy costs*. *Frontier in Science*, 2:1411259.

Khangura, R., Ferris, D., Wagg, C., & Bowyer, J. (2023). *Regenerative Agriculture—A Literature Review on the Practices and Mechanisms Used to Improve Soil Health*. *Sustainability*, 15(3), 2338.

Li, X., Storkey, J., Mead, A., Shield, I., Clark, I., Ostler, R., Roberts, B. & Dobermann, A. (2023) *A new Rothamsted long-term field experiment for the twenty-first century: principles and practice*. *Agronomy for Sustainable Development*, 43, 60.

Lotter, D.W., Seidel, R. & Liebhardt, W. (2003) *The performance of organic and conventional cropping systems in an extreme climate year*. *American Journal of Alternative Agriculture*, 8(3), 146-154.

Lumsden, C.L., Jägermeyr, J., Ziska, L. & Fanzo, J. (2024) *Critical overview of the implications of a global protein transition in the face of climate change: Key unknowns and research imperatives*. *One Earth*, 7(7), 1187-1201.

Mackay, I.J, Horwell, A., Garner, J. & White, J. (2011) *Reanalyses of the historical series of UK variety trials to quantify the contributions of genetic and environmental factors to trends and variability in yield over time*. *Theoretical and Applied Genetics*, 122(1), 225-238.

MacLeod, M., Eory, V. & Barnes, A. (2024) *Clean Growth through Sustainable Intensification*. MACC Fiches. Scotland's Rural Colleges (SRUC).

Madau, F.A., Arru, B., Furesi, R., & Pulina, P. (2020). *Insect Farming for Feed and Food Production from a Circular Business Model Perspective*. *Sustainability*, 12(13), 5418.

Maine, N., Lowenberg-DeBoer, J., Nell, W.T. & Alemu, Z.G. (2010) *Impact of variable-rate application of nitrogen on yield and profit: a case study from South Africa*. *Precision Agriculture* 11, 448–463.

Massel, K. (2023) *What's the latest on GMOs and gene-edited foods – and what are the concerns? An expert explains*. *The Conversation*. Available at: <https://theconversation.com/whats-the-latest-on-gmos-and-gene-edited-foods-and-what-are-the-concerns-an-expert-explains-204275>

Monteiro, A., Santos, S., & Gonçalves, P. (2021). *Precision Agriculture for Crop and Livestock Farming—Brief Review*. *Animals*, 11(8), 2345.

Moore, G. (2024) *Enifer takes giant step closer to scaling up aquafeed mycoprotein production*. *Fish farming expert (FFE)*. Available at: <https://www.fishfarmingexpert.com/enifer-skretting/enifer-takes-giant-step-closer-to-scaling-up-aquafeed-mycoprotein-production/1610979>

Mueller, M.L. & Van Eenennaam, A.L. (2022) *Synergistic power of genomic selection, assisted reproductive technologies, and gene editing to drive genetic improvement of cattle*. *CABI Agriculture and Bioscience*, 3(13).

National Academies of Sciences, Engineering, and Medicine (NASEM) (2016) *Genetically Engineered Crops: Experiences and Prospects*. Washington, DC: The National Academies Press.

Natural England (2009) *Environmental impacts of land management (NERR030)*. Available at: <https://publications.naturalengland.org.uk/publication/30026>

O'Connor, J., Skeaff, S., Bremer, P., Lucci, G., & Miroso, M. (2023) *A critical review of on-farm food loss and waste: future research and policy recommendations*. *Renewable Agriculture and Food Systems*, 38, e24.

O'Donoghue, T., Minasny, B., & McBratney, A. (2022). *Regenerative Agriculture and Its Potential to Improve Farmscape Function*. *Sustainability*, 14(10), 5815.

Oh, S., and Lu, C. (2022) *Vertical Farming - Smart Urban Agriculture for Enhancing Resilience and Sustainability in Food Security*. *The Journal of Horticultural Science and Biotechnology*, 98(2): 133–40.

Pellegrino, E., Bedini, S., Nuti, M. & Ercoli, L. (2018) *Impact of genetically engineered maize on agronomic, environmental and toxicological traits: a meta-analysis of 21 years of field data*. *Scientific Reports*, 15:8(1):3113.

Pexas, G., Doherty, B. & Kyriazakis, I. (2023) *The future of protein sources in livestock feeds: implications for sustainability and food safety*. *Frontiers of Sustainable Food Systems*, 7:1188467.

Rasool, K., Hussain, S., Shahzad, A., Miran, W., Mahmoud, K.A., Ali, N. & Almomani, F. (2023) *Comprehensive insights into sustainable conversion of agricultural and food waste into microbial protein for animal feed production*. *Reviews in Environmental Science and Bio/Technology*, 22, 527–562.

Read, Q.D., Brown, S., Cuéllar, A.D., Finn, S.M., Gephart, J.A., Marston, L.T., Meyer, E., Weitz, K.A. & Muth, M.K. (2020) *Assessing the environmental impacts of halving food loss and waste along the food supply chain*. *Science of The Total Environment*, 712, 136255.

Röös, E., Bajželj, B., Smith, P., Patel, M., Little, D. and Garnett, T. (2017) *Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures*. *Global Environmental Change*, 47, 1-12.

Royal Society (2023) *Enabling genetic technologies for food security: Policy briefing*. Available at: [www.royalsociety.org/genetic-technologies-uk](http://www.royalsociety.org/genetic-technologies-uk)

Royal Society (2024) *Is it safe to eat GM crops?*. Available at: <https://royalsociety.org/news-resources/projects/gm-plants/is-it-safe-to-eat-gm-crops/>

Savills (2021) *Regenerative Agriculture Spotlight*. Available at: <https://pdf.euro.savills.co.uk/uk/rural--other/spotlight---regenerative-agriculture-2021.pdf>

Savills (2023) *Can vertical farms compete?* Available at: [https://www.savills.co.uk/research\\_articles/229130/343469-0#:~:text=A%20premium%20vertical%20farm%20can,-tech%2C%20closely%20controlled%20system](https://www.savills.co.uk/research_articles/229130/343469-0#:~:text=A%20premium%20vertical%20farm%20can,-tech%2C%20closely%20controlled%20system)

Sawyer, E., Yesuf, G., Wade, R. & Yildirim, A. (2023) *Understanding & Evaluating On-Farm Loss and Waste in The UK: A report for the Transforming UK Food Systems SPF Programme*. Available at: <https://ukfoodsystems.ukri.org/wp-content/uploads/2023/08/Understanding-Evaluating-On-farm-loss-and-waste-in-the-UK.pdf>

Soto, I., Barnes, A., Balafoutis, A., Beck, B., Sánchez, B., Vangeyte, J., Fountas, S., Van der Wal, T., Eory, V. & Gómez-Barbero, M. (2019) *The contribution of precision agriculture technologies to farm productivity and the mitigation of greenhouse gas emissions in the EU*. European Commission.

Simon, W.J., Hijbeek, R., Frehner, A., Cardinaals, R., Talsma, E.F. & van Zanten, H.H.E. (2024) *Circular food system approaches can support current European protein intake levels while reducing land use and greenhouse gas emissions*. *Nature Food*, 5, 402-412.

Sowmya, C., Anand, M., Indu Rani, C., Amuthaselvi, G. & Janaki, P. (2024) *Recent developments and inventive approaches in vertical farming*. *Frontiers in Sustainable Food Systems*, 8:1400787.

Systemiq (2021) *National Food Strategy: understanding the impact of changing food production and diets on food prices and affordability*. Available at: <https://www.nationalfoodstrategy.org/wp-content/uploads/2021/09/Evidence-Impact-of-production-changes-on-food-prices-1.pdf>

Touliatos, D., Dodd, I.C. & McAinsh, M. (2016) *Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics*. *Food and Energy Security*.

UK Parliament (1998) *Genetically Modified Foods*. Parliamentary Office of Science and Technology. Available at: <https://www.parliament.uk/globalassets/documents/post/pn115.pdf>

UKRI (2022) *Alternative Proteins: Identifying UK Priorities: A roadmap for the future of the alternative protein sector in the UK*. Available at: <https://www.ukri.org/wp-content/uploads/2022/06/IUK-100622-AlternativeProteinsReport-FINAL.pdf>

U.S. Department of Agriculture (USDA) (2024) *List of Bioengineered Foods*. Available at: <https://www.ams.usda.gov/rules-regulations/be/bioengineered-foods-list>

Van Delden, S.H., SharathKumar, M., Butturini, M. Graamans, L.J.A., Heuvelink, E., Kacira, M., Kaiser, E., Klamer, R.S., Klerkx, L., Kootstra, G., Loeber, A., Schouten, R.E., Stanghellini, C., van Ieperen, W., Verdonk, J.C., Violet-Chabrand, S., Woltering, E.J., van de Zedde, R., Zhang, Y. & Marcelis, L.F.M. (2021) *Current status and future challenges in implementing and upscaling vertical farming systems*. *Nature Food*, 2, 944-956.

Van Gerrewey, T., Boon, N., & Geelen, D. (2022). *Vertical Farming: The Only Way Is Up?* *Agronomy*, 12(1), 2.

Vaughan, A. (2022) *Gene-edited food is 5 years away in England, says government scientist*. *New Scientist*. Available at: <https://www.newscientist.com/article/2305284-gene-edited-food-is-5-years-away-in-england-says-government-scientist/>

Verbeke, W., Spranghers, T., De Clercq, P., De Smet, S., Sas, B. & Eeckhout, M. (2015) *Insects in animal feed: Acceptance and its determinants among farmers, agriculture sector stakeholders and citizens*. *Animal Feed Science and Technology*, 204, 72-87.

WWF (2022) *The Future of Feed: How Low Opportunity Cost Livestock Feed Could Support A More Regenerative Uk Food System*. Available at: [https://www.wwf.org.uk/sites/default/files/2022-06/future\\_of\\_feed\\_full\\_report.pdf](https://www.wwf.org.uk/sites/default/files/2022-06/future_of_feed_full_report.pdf)

WWF-UK (2022) *Hidden waste: the scale and impact of food waste in primary production*. Available at: <https://www.wwf.org.uk/our-reports/hidden-waste>

Zu Ermgassen, E. K. H. J., Kelly, M., Bladon, E., Salemdeeb, R. & Balmford, A. (2018) *Support amongst UK pig farmers and agricultural stakeholders for the use of food losses in animal feed*. *PLoS ONE*, 13(4): e0196288.

A stylized graphic of a topographic map, consisting of several concentric, irregular, light green lines that resemble contour lines, positioned on the left side of the page.

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