Appendix 5: 1112-00006A - AgriFoodTure - Roadmap for Sustainable Transformation of the Danish Agri-Food System

Roadmaps for mission-driven green research and innovation partnerships (Innomission-roadmaps)

Innomission partnerships: Translating mission roadmaps into sustained actions

The call for mission-driven green research and innovation partnerships is the second phase in Innovation Fund Denmark's (IFD) Innomission program. Phase one generated roadmaps for each of the four missions (https://innovationsfonden.dk/da/programmer/groenne-missioner). Phase two now asks for proposals to form Innomission partnerships to drive action based on the directions outlined in the roadmaps.

During phase one Innovation Fund Denmark received 12 roadmaps within the four mission areas. Of these 12 roadmaps, six roadmaps were selected by the IFD Board of Directors to provide direction to the partnerships in designing action plans. The six roadmaps are described in the call for innomission-partnerships and shown in its full length in these appendices.

AgriFoodTure

ROADMAP FOR SUSTAINABLE TRANSFORMATION OF THE DANISH AGRI-FOOD SYSTEM

AgriFoodTure
ROADMAP FOR SUSTAINABLE TRANSFORMATION OF THE DANISH AGRI-FOOD SYSTEM

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May 2021

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INTRODUCTION

Background The global human population has increased from 1 billion in 1800 to 7.9 billion today and although the growth rate has diminished during recent decades, the population is expected to reach 9.7 billion by 2050. Securing food for this increasing and progressively wealthier population requires a dare effort, and the demand for protein-rich diets is expected to double by 2050. This is projected to require an increase in overall food supply of 45% by 2050. Importantly, while solving this challenge, we should simultaneously facilitate a green transition of the food sector. Agriculture is globally a major factor contributing to pressures on planetary boundaries affecting biogeochemical cycles, climate, ecosystems, and biodiversity. Agricultural activities are thus by far the main contributor to nutrient loadings, freshwater consumption, land use change, and biodiversity decline, and contribute about a third to greenhouse gas (GHG) emissions. The efforts to reduce the pressures from agriculture while enhancing a nutritious food supply constitute a major and extraordinarily complex challenge for current and future generations. The measures to increase production should go hand in hand with national and global efforts to dramatically reduce emission of GHGs, reduce environmental issues related to pesticide and nutrient runoff and ammonia emissions, halt the current fast rate of local and global species extinctions, and set aside current agricultural land for the benefit of environmental and biodiversity protection.

To reach these goals in Denmark, we argue for the need of a highly coordinated effort involving collaboration between universities in Denmark and abroad, GTS industry, institutes, local and national authorities, and non-governmental organizations. The task is too big and too complex to solve in individual groups with specialised technologies or within specific disciplines. Creative, transformative thinking is a prerequisite for success. It demands considerable international outlook and collaboration between partners and key players that may not have worked together previously, including researchers from natural, technical, and social sciences and humanities.

We propose that for the green transition of food industry, agriculture, and land use to be successful, a holistic view is needed and the wishes and demands of consumers and citizens are key in this respect. Future food systems constitute complex socio-ecological systems that involve cross-level and cross-scale interactions between human and natural components and major social outcomes, such as ecosystem services, social welfare, and food security. In contrast to the traditional "farm-to-fork" approach focusing on increased production, food safety, documentation, etc. at each step from soil to table, a novel approach proposes a "fork-to-farm" conceptual framework. Here the point of departure is consumer demands and preferences, societal and political demands, co-development processes with producers, value chain actors and retailers, with the purpose of creating sustainable and purposeful food value chains. This involves living labs, where innovation is driven by farmers, researchers, and civil society in a collaborative effort. Such initiatives are needed across the different farming paradigms, whether this concerns conventional farming systems or organic farming, or involves aspects of concepts ›

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› such as conservation agriculture, agroforestry, permaculture and agroecology. We have chosen to focus this roadmap on the strategic goals that Innovation Fund Denmark has listed in the call. Within these goals, we have assessed that the largest contributions are within the primary agricultural production and in the development of technologies and products in new food value chains.

The ideas and visions proposed in this roadmap will provide knowledge and knowhow relevant for the green transition worldwide, requiring international collaboration and sharing of knowledge, experiences, and knowhow. Denmark has a long tradition for innovation and research within food and agriculture and strong private-public partnerships supporting viable businesses with global outreach. This puts Denmark in a unique position to become a driver for the green transition of food, agriculture and land use providing national and international solutions to overarching challenges of current and future generations, namely securing nutritious food for a growing human population while simultaneously:

1. securing jobs based on innovative and sustainable solutions benefitting Danish exports and economy
2. reducing environmental and climate impacts of food and agricultural production systems
3. increasing food supply in support of growing demands
4. reversing the decline in pollinators and loss of biodiversity in general, including endangered species, and
5. setting aside land for multiple functions, including climate change adaptation, nature and recreational use.

Our roadmap contributes to at least 9 of the 17 United Nations Sustainable Development Goals.

This roadmap is based on collaborative efforts with contributions from more than 200 researchers from Danish universities, industry, and NGOs. It outlines gaps, solutions, and Danish strongholds to achieve the overall goals of a green transition of agriculture and land use. We argue that the agricultural and land use sector is key to solving these challenges, but that profound and highly needed transformations of the sector require a change of the entire and complex food system and its interlinkages with land use and human demands (Figure 1). Sustainable solutions should be developed in an inter-connected web of land use management, disruptive plant and animal-based food production, novel biotechnological solutions, and new protein sources, while supporting the entire value chain and related business models sensitive to consumer demands. A circular perspective to the technologies and the economy is required, in which biomass production is maximised and upgraded for a range of different uses increasing overall area productivity, and in which nutrients are recycled to the agricultural land thus reducing needs for external inputs.

Denmark as a leader for the sustainable transformation of the agri-food system Denmark has a unique potential to become an important driver within the green transition of agriculture, land use and food clusters. We have a particularly strong international image in terms of sustainability, animal welfare, food quality standards and low environmental impact of food production. 55% of decision-makers in an international evaluation stated that products and solutions from the Danish food clusters are among the most sustainable in the world. It is also clear that there is an untapped potential for increasing the collaboration across key players and that doing so will have the potential to further spark the sustainable development of Danish agriculture and food industry, and position Denmark as a front-runner of an innovative and disruptive green transition of food production internationally, powering a new generation of green global export opportunities.

Firstly, this potential derives from a long tradition of collaboration across the food value chain and from building an innovative and knowledge-intensive sector based on close collaboration between large multinational companies and small innovative start-up businesses, authorities, innovation clusters, NGOs, and research institutions.

Secondly, Denmark has a proven track record of responding constructively to challenges within the sector. Examples include major reductions in use of pesticides and antibiotics in Danish agriculture compared to similar countries, 50% reduction in N loads to the aquatic environment over 30 years, and a doubling of organically farmed land within the last 12 years.

Thirdly, we have a unique tradition for data generation and technological development and implementation at all levels in the production system from field to fork, including efficient use of resources throughout the product chains. These include unique collaboration among actors that make data available ›

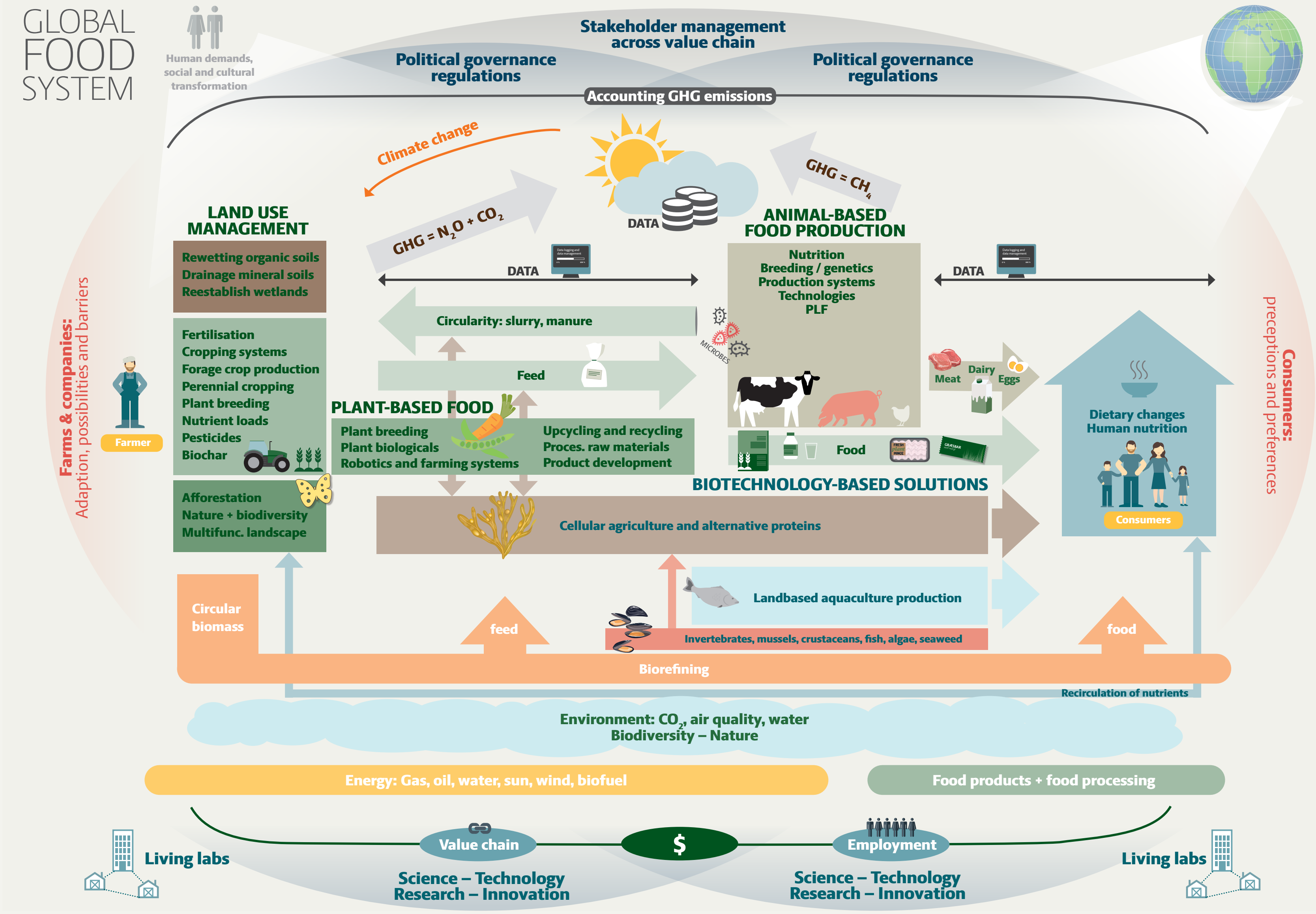

FIGURE 1
Global food system map illustrating the complex interplay between animal and plant-based food production, land use and management, and biotechnological innovations. Solutions can only be obtained in collaboration between sectors and requires considerable consumer involvement.

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for research and development, e.g., for selective breeding in animals and plants. Danish assets also include development of new precision farming technologies facilitating a management approach that focuses on real-time observations, measurements, and responses to variability in crops and animals, and a strong position in the food ingredients and biotechnology sector.

Fourthly, climatic conditions, soil quality and the flat Danish landscape make Denmark a superior country for farming, even under projected climate changes. The collaborative approach between research institutions, industries and the public sector makes joint efforts for sustainable solutions, based on negotiated changes in land use and management, feasible for the benefit of multiple functions.

Considering the strong platform that we stand on and taking departure in new innovative ideas and disruptive thinking, Denmark is in a unique position to develop and implement the green transition of the agricultural sector and food industry.

MEASUREMENT OF SPECIFIC IMPACT OF ROAD-MAP ON MISSION GOALS

The technologies and solutions presented in this roadmap show how combined efforts enable reaching the national goal of 70% reduction of GHG emissions by 2030 with no leakage effects, and further contributing to reducing global GHG emissions towards 2050. This reduction can only be reached by a combination of initiatives and disruptive innovative solutions. Simultaneously with reducing global GHG emissions we should provide solutions that allow reaching goals for biodiversity and pollution. This demands development and implementation through disruptive innovative solutions. To bridge knowledge gaps, we need to explore different pathways for the future development of the agriculture and food sector. This endeavour will allow us to reach inflection points from where we can make substantial and sustained progress towards achieving the 2030 goals and fulfilling the 2050 vision. We have identified four major tracks which together will contribute to reaching the 2030 and 2050 goals and visions:

- A: Land use and management
- B: Animal-based food production
- C: Plant-based food production
- D: Biotechnology-based food production and alternative protein sources

In addition to the four tracks, cross cutting aspects are described in a common section.

For each of these tracks we describe the knowledge and innovation needed to secure a range of solutions that will allow reaching the 2030 and 2050 goals. We envision that each track will form a solid basis for the establishment of strong and dedicated partnerships, allowing researchers, organisations and companies with specific expertise, interests and business models to focus on strengthening research, innovation and implementation within and across their fields. These partnerships will be complementary and should be coordinated to ensure that we reach the goals and deliver what is needed for climate, biodiversity, environment, and food security, jobs and export agendas and taking into account consumer demands and involvement (Figure 2).

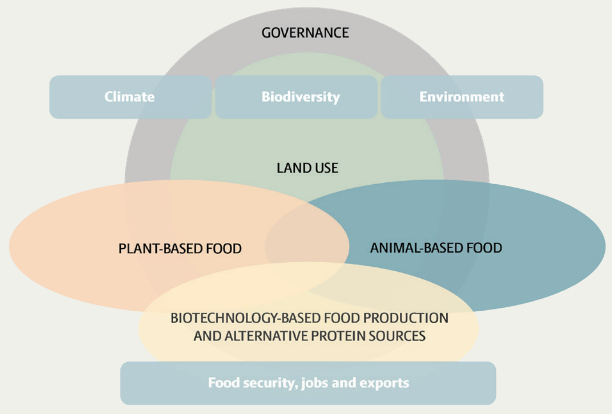

FIGURE 2
A green transition of the agriculture and food sectors will depend on strong collaboration between researchers and commercial operators across the different tracks. Utilising the potential for synergy will provide tools and solutions to reach the goals for climate, biodiversity, and environment, while contributing to food security, jobs, and exports.

Often dilemmas arise because what is needed to obtain one goal, such as increased biodiversity may compromise other goals, such as reducing GHG or reduced pesticide and fertiliser use, and diminish productivity and thereby potentially food security, jobs, and exports. There is also the risk that

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› diminishing productivity can lead to destruction of biodiversity and larger GHG emissions in other countries (the leakage effect), since global food demands continue to rise. Thus, easy solutions do not exist, and there is a need for the novel ideas and collaborative efforts represented in this roadmap. Doing so will allow us to:

1. reach the goals of 70% reduction of GHG emissions by 2030 compared with 1990 levels, carbon neutrality by 2050 at the national level without leakage effects, while enabling additional reductions globally,
2. reach 24% reductions of ammonia emissions by 2030 as compared with 2005 levels,
3. reach the ambition to become world leading within circular economy by 2030, and
4. contribute with our share in turning 30% of Europe's land into protected areas, reduce pesticide use by 50%, reverse the decline of pollinators/endangered species and plant millions of trees.

The current annual GHG emissions from primary agricultural activities in Denmark amount to 17.4 Mt CO_2-eq., equalling 35% of total Danish GHG emissions. Roughly 33% of emissions are associated with drainage of peatlands, 38% with enteric fermentation and manure management from livestock production, 22% with crop production and 7% with fossil energy use. The ideas will reduce emissions by developing and implementing technologies across all these emission sources; however, it will not be possible to eliminate all emissions and hence there is a need for offsetting emissions through enhanced carbon storage in soils and vegetation, estimated at about 2.0 Mt CO_2-eq. in 2030 and 4.3 Mt CO_2-eq. in 2050. Emissions from drained peatlands will be reduced through rewetting, which will also support reductions in nutrient leakages to the aquatic environment enhancing nature areas and biodiversity. Emissions from livestock will be reduced through improved feeding, targeted breeding, additives, and new manure technologies, and in the longer term also through partly substituting animal-based food with plant-based food and alternative protein-based foods from biotech solutions. Emissions from crop production will be reduced through developing novel diverse arable cropping systems and food and feed production systems based to a greater extent on perennial crops, which will reduce nitrous oxide (N_2O) emissions and lower needs for pesticides through targeted breeding, novel fertilisation systems and precision technologies aided by sensors, AI, robotics, remote sensing, and biologicals. This will be further supported by increased circularity in biomass use and nutrient cycling at farm, landscape and societal scales lowering the needs for external inputs and enhancing soil carbon, e.g., through use of biochar from pyrolysis. It will be supported by technological solutions that convert conventional food processing industries into resource optimized, sustainable and climate neutral operators recycling excess nutrients to agricultural land. These efforts will also contribute to enhancing resilience of the agricultural production systems to negative impacts of climate change and extreme events.

The current loadings of nitrogen (N) and phosphorus (P) from land use greatly exceed the targets under the Water Framework Directive for good ecological status. Meeting these targets will be achieved by reducing nutrient leakages from agricultural systems through greater N uptake and precision fertilisation and by increasing landscape retention of the nutrients through wetland restoration, constructed wetlands and spatially targeted conversion of agricultural land to forestry and nature. This may result in a reduction of current agricultural land area by 15-20%. This conversion to nature and forestry will support the nature and biodiversity targets, and together with more biodiverse arable land and increased use of perennial cropping systems and agroforestry, this will enable the biodiversity targets to be achieved. Substantial reductions in ammonia emissions will be achieved through improved livestock systems, manure management and new fertilisation systems.

The reduction of about 20% in agricultural land area along with a growing global food demand of 45% by 2050 calls for an increase in food productivity of almost 60% if Denmark is to maintain its current share of global food production. This requires focus on increased efficiency in the primary production of both cropping and livestock systems, enhanced use of circular technologies for livestock feed supply, as well as increased focus on plant-based food and alternative biotech protein-based foods with greater area productivity. By developing and implementing technologies within these different tracks, Danish food and agroindustry will not only solve a large part of the sustainability challenges for the Danish society and landscapes, but also contribute greatly to the development of global sustainable agriculture and land use.

In the following sections each of the four tracks and a common cross-cutting section are described with their own 2050 vision and 2030 goals, including an identification of their individual key challenges, inflection points and gaps. Each of the tracks will define relevant **milestones, timeline, and success criteria** to assist the achievement of the goals and outline key workstreams and activities for the subsequent partnerships.

TRACK A **LAND USE AND MANAGEMENT**

Background The land area in Denmark is a highly cultivated landscape, with 60% agriculture, 12% urban areas and infrastructure, 14% forests and 14% nature areas. About 19% of the agricultural area is used for organic farming, with a high proportion used for dairy farming or extensive grazing. Of the 2.6 mill. ha in agricultural production, 0.17 mill. ha are drained organic soils with estimated annual GHG emissions of 5.7 Mt CO_2-eq. The agricultural land is the source of N_2O emissions corresponding to 4.3 Mt CO_2-eq annually.

The many sustainability targets can only be achieved through changes in landscape structure, functions, management, and associated governance. This involves efforts related to land use (rewetting organic soils, constructed wetlands, drainage of mineral soils), agricultural land management (arable, forage and perennial crops, fertilisation, plant breeding, nutrient cycling) and landscape and biodiversity management (afforestation, land sparing and management for biodiversity, governance). The objective of this track is to develop technological and governance solutions that will allow for a carbon neutrality at the landscape level in 2050 and large GHG reductions by 2030 coupled with reductions in N and P loads to the aquatic environment, as well as substantial reductions in pesticide use, and a landscape that supports biodiversity in all major Danish ecosystem types. The objective is further to develop the foundation for documenting progress and to develop governance structures to support rapid transitions towards sustainable land use and management.

Key activities and work streams

Cli	Env	Inn	Nat	Barr	
				G	Rewetting of organic soils
				C	Drainage of agricultural mineral soils
				GC	Re-establishing and constructing wetlands
				C	Fertilisation management for lower nitrous oxide and nitrate leaching
				CL	Arable cropping systems
				C	Forage crop production
				LR	Perennial cropping systems
					Plant breeding for sustainability
				GC	Afforestation and forest management [for sustainability and biodiversity]
				GC	Nature and biodiversity protection in the agricultural landscape
				G	Multifunctional landscape planning and governance
				CL	Circular biomass and nutrient flows at farm and landscape scales

Effects on Climate (**Cli**), Environment (**Env**), Growth and Innovation (**Inn**), and Nature (**Nat**) from key activities within the track. Relative contribution is assessed by the colour intensity: darker is higher contribution than lighter, white is no contribution. In addition, barriers (**Barr**) are identified and include **C** Cost; **G** Governance and Legislation; **L** Logistics; **R** Resistance to change in the sector.

Backtracking (gaps, challenges, and inflection points)

Across land use of organic and mineral soils, emission of CO_2 relates to the mineralisation of organic carbon and associated N_2O emissions. Reestablishment of wetlands close to watercourses is a valuable tool for reducing N discharges but is in some cases associated with methane emissions and increased P discharges to the aquatic environment, and there is a need to develop technologies and measures to allow cost-efficient rewetting with maximum GHG reductions, low environmental impact and supporting biodiversity. The importance of drainage status of mineral soils for GHG emissions is not well understood. There is a need for development of filter-based solutions (e.g., constructed wetlands) to protect the aquatic environment from N and P loads.

In cropping systems, reduction of N_2O emissions from mineral and organic fertilisers, and crop residues will be prioritised. First, cropping systems should be more N efficient to prevent losses, including leaching and N_2O, and to enhance soil carbon sequestration. This will entail development of new fertilisation schemes and technologies. Increased primary productivity is possible through temporal and spatial diversification of cropping systems, supporting resilience, biomass production and resource utilisation. This involves better use of the entire growing season with increased use of perennial crops, supporting biodiversity and enhancing productivity. Resilience and diversification will minimise needs for pesticides and reduce crop losses from diseases and pests. Increased production efficiency will also be supported through breeding by improving digestibility of feed for livestock, and by im- ›

Track A Land use and management

› proving exploitation of plant nutrients, both in terms of plant uptake from the soil and in terms of nutrition for livestock and food. Crop nutrition needs to be seen in a circular perspective, where a larger part of the nutrients (N and P) is recovered from the landscape and in waste streams and recycled as fertiliser to the field. There is further need for enhancing soil carbon to offset other GHG emissions, and some of this will come from application of biochar from pyrolysis of biomass and wastes. These efforts need to support soil quality and health increasing resilience of the cropping systems to environmental stress.

Land use also deals with landscape planning and governance, including afforestation, and nature and biodiversity protection. This involves aligning concerns for biomass production with climate and environmental protection and the recovery and maintenance of biodiversity across landscapes. Reaching the biodiversity goal requires setting aside large and connected areas for nature protection, restoration of natural and dynamic processes, reducing effects from multiple environmental pressures, maximising biodiversity within agricultural production systems, and implementation through transformation of incentives (subsidies) and legal frameworks for nature and agricultural management. Cropping systems can accommodate more biodiversity through 1) diversified cropping systems, 2) agri-environmental schemes that maximise biodiversity elements within agricultural production systems, and 3) agricultural systems with complementary functional traits characterizing high biodiversity ecosystems which stimulate productivity and facilitate stability. Trees and forests capture and store carbon, provide renewable materials for versatile use, and provide habitats for biodiversity. Landscape planning and governance solutions encompass at least three general elements: 1) planning the best available distribution of functions in landscapes, 2) developing regulative measures and incentives that support the green transition both in relation to technological innovations, land distribution, and landscape management, and 3) establish institutional structures that make it possible to openly discuss and justify the selected measures and planning solutions among citizens, authorities and NGOs who are involved in or affected by the transitions.

Research and innovation needs The development of multifunctional land use and management requires improved quantification of how land use and agricultural production systems influence emissions (GHG, N, P, etc.) from different soils, cropping systems, fertiliser systems, and the effect of landscape structures and hydrological conditions on emissions. There is also a need for development and implementation of monitoring protocols to fully document and monitor biodiversity aspects of land use elements. This requires novel technologies to develop and improve mapping tools for supporting monitoring, reporting and verification (MRV) requirements in support of the regulation of the many sustainability requirements linked to land use and management.

LAND USE

- Improved quantification of GHG emissions from rewetting different types of organic soils, and quantified effects on P losses over time (TRL=8, 2030) to effectively map suitable land for rewetting with maximum effects on GHG emission reductions.
- Knowledge basis for rewetting 100,000 ha of low-lying agricultural soils (TRL=8, 2030) and rewetting all organic soils (SRL=9, 2050) for substantial reductions in GHG emissions and nutrient loadings.
- Knowledge basis for establishing 5,000 (TRL/SRL=9, 2030) and 10,000 (2050) constructed wetlands and at least 5,000 (TRL/SRL=9, 2030) and 10,000 (2050) saturated and intelligent buffer zones to reduce N and P loads.
- Formulation (TRL=5, 2025) and testing (TRL=7, 2030) of new measures to reduce N_2O emissions from poorly drained mineral soils and implementation to reduce GHG emissions by 0.4 mill. ton CO_2-eq/yr (SRL=9, 2050).

AGRICULTURAL LAND MANAGEMENT

- Disaggregated N_2O emission factors for fertiliser types (TRL=8), nitrification inhibitors and cultivation methods (TRL=8), revised model for predicting emissions from fertilisation (TRL=7), and environmental risk assessment for nitrification inhibitors (TRL=9) (2025).
- Advanced modelling approach for predicting N_2O emissions from fertilisation based on soil and environmental factors and fertiliser type (TRL=7, 2030).
- A 70% reduction in N_2O emissions from mineral and organic fertilisers through adoption of improved fertilisers and timing of fertilisation documented through precision farming technologies (TRL/SRL=9, 2050). ›

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- Arable cropping systems with early harvest of cereals, improved cover crops and harvesting of cover crop for biorefining with lower N_2O emissions and N leaching and greater productivity developed (TRL=7, 2030) and implemented (TRL/TRL=9, 2050).
- Soil management solutions for improved soil structure with lower N_2O emissions developed (TRL=5, 2025), demonstrated (TRL=6, 2030) and implemented (TRL/SRL=9, 2050).
- Arable cropping systems with greater functional species and variety diversity managed through novel technologies (robotics, drones, sensor systems, remote sensing) for enhanced resource use and resilience to biotic and abiotic stresses as well as lower GHG emissions developed (TRL=5, 2025), tested (TRL=6, 2030) and implemented (TRL/SRL=9, 2050).
- Grassland based forage crop production systems with multispecies mixtures and managed with low soil compaction, low N and GHG emissions, high feed quality, no pesticides and precision farming (robotics, drones, sensor systems, remote sensing) developed (TRL=5, 2025), tested (TRL=6, 2030) and implemented (TRL/SRL=9, 2050).
- Novel productive perennial cropping systems (including agroforestry) for food and feed with low GHG emissions and N losses, low pesticide use, and greater biodiversity developed (TRL=5, 2025) and tested/implemented on 10% (TRL=8, 2030) and 40% (TRL/SRL=9, 2050) of the agricultural land.
- Plant breeding supporting greater resilience to stress, greater resource use efficiency and value for feed and food in annual and perennial crops and cover crops (TRL=7, 2030) and specific reductions in N_2O emissions through plant-microbe interactions (TRL=5, 2030; TRL=8/9, 2050).
- Technologies based on biorefining to upcycle biomass from various parts of the landscape to food, feed, and materials and for recycling nutrients in valuable fertilisers for substituting external inputs developed (TRL=5, 2025), tested (TRL=7, 2030) and implemented (TRL/SRL=9, 2030).
- Technologies and management for biochar application in mineral soils that sustain greater crop yields and lower nutrient losses while sequestering soil carbon developed (TRL=5, 2025) and implemented (TRL/SRL=8/9, 2030).

AFFORESTATION, BIODIVERSITY, AND GOVERNANCE

- Establishment of methods for documenting ecosystem services and functions, including GHG, nutrient loads and biodiversity, of forest and nature lands (TRL=7, 2025).
- Development and implementation of smart systems for tree species in forests and agroforestry systems in accordance with certifications and standards (TRL=8, 2030).
- Establishment and evaluation of optimal methods for restoration of natural and dynamic processes across all Danish ecosystems to enhance biodiversity (TRL=7, 2025), and tools to advice local managers under given landscape setting and environmental conditions (TRL/SRL=8, 2030).
- Methods and tools to prioritise large and connected areas for recovery and maintenance of biodiversity (land sparing) as well as tools to protect and facilitate biodiversity on agricultural land (land sharing) developed (TRL=5, 2025) and evaluated and implemented (TRL/SRL=8, 2030).
- A concept for advising and counselling on speedy land distribution for enhanced biodiversity, higher biomass production, reduced nutrient loads and GHGs based on spatial data, detailed data from automated observation systems (IoT, drones, remote sensing), and IT support for decision making developed (TRL=6, 2025) and implemented at municipality level (SRL=8, 2030).

Impact of the track on strategic goals and value creation The optimised land use and management will increase biomass production for sustaining agricultural feed and food production as well as reduce GHG emissions, reduce pesticide use, reduce N and P loads to the aquatic environments and create larger coherent land areas set aside for biodiversity protection and recreational value. These efforts are estimated to meet the needs for the agricultural climate targets as well as provide reduced environmental impacts and biodiversity protection. However, this requires substantial changes in land use and agricultural cropping systems. The greater productivity and reduced needs for external inputs in the cropping systems will improve profitability of these systems. The largest part of the value creation will come from three pathways: 1) meeting sustainability targets within agricultural land use

Track A Land use and management

› and management will become the license to operate for farming as well as a key market driver, 2) improved value of landscapes supporting new functions and jobs linked to recreation and tourism, and 3) exports of technologies within plant breeding, crop and nutrient management, technologies for smart management of cropping systems, and biomass processing.

Risk management and alternatives Measures applied for the various purposes must be verified experimentally to document if they have the expected and proposed effect, including how they are applied in practice. For this, a diverse range of test and demonstration centres (living labs) is critical. This is needed, also because current knowledge is challenged by changing climatic conditions and by changing social and market conditions. There are several risks that may arise within research and innovation to support the transitions, which in general may involve: 1) insufficient effects of measures, 2) lower agricultural productivity with suggested measures, 3) difficulties in adopting measures, 4) negative side-effects of measures, 5) low cost-effectiveness of measures, 6) incompatibility with current land use and agricultural systems, and 7) unwillingness among actors for necessary transformations. The measures needed to manage these risks vary and actions need to target the specific concerns based on a multi-actor analysis, and this will require close monitoring of progress based on critical decision points.

Danish strongholds and financial aspects Denmark has a strong science basis in managing agricultural GHGs and nutrient flows in agricultural landscapes, and this is linked to strong innovation environments and globally active companies within plant breeding (e.g., DLF, DSV Denmark, Nordic Seed, Danespo, Sejet) and farm machineries and smart crop management (e.g., AgroIntelli, Samson Agro, AGCO, Field-Sense). Denmark has strong science basis in biodiversity and nature restoration, and the use of novel technologies to monitor changes, and there are also companies related to these aspects (e.g., FaunaPhotonics, Rambøll, HedeDanmark). Further, Denmark has strong competences in mapping soil and hydrological conditions affecting environmental impacts (e.g., FOSS, Aarhus GeoInstruments).

The annual financial needs for research and innovation are estimated at around 1.5 billion DKK, a substantial part of which will also involve pilot scale and upscaling activities. In addition, there will be a need for funds that support land purchases and land infrastructure developments for rewetting organic soils, afforestation and re-establishing nature areas estimated at 1.5 billion DKK annually.

TRACK B **ANIMAL-BASED FOOD PRODUCTION**

Background The vision for this track is to identify, develop and implement activities, which will ensure a production of the most climate efficient animal-based food products in the world to accommodate and meet a growing worldwide demand for animal-based proteins and foods. A climate friendly diet will therefore also in the future include animal-based products such as dairy, meat and eggs. This will be achieved through supporting this transition for all parts in the production chain to enhance value creation and economic activity in the animal sector. Before 2030 farmers have adapted to climate incentive strategies and know how to maximise value creation under such systems. Human perspectives and knowledge about consumer preferences and how to induce changes among consumers towards a sustainable climate-smart animal-based diet will also be established already in 2030. Documentation and datasharing e.g., use of big data and technologies through an established common data platform collecting data from sensors and other sources has been established in 2030, which will enable intensive monitoring, control and decision support for precision management thereby increasing resource efficiency and waste utilisation as well as reducing emissions. In 2030 animal-based food production will have reduced the climate footprint achieved by:

1. Minimum 50% reduction in direct methane emissions due to a reduced production of enteric methane without compromising productivity, accompanied by at least a 40% reduction in the carbon footprint of the dairy and meat products. This will be facilitated by nutritional and genetic ›

Track B Animal-based food production

interventions as well as first generation feed additives. Furthermore, a 25% reduction in the carbon footprint of products from the monogastric livestock production related to areas such as improved feed efficiency and optimized herd management will be achieved.

2. 10% reduction in excretion of N from livestock production facilitating a 15% reduction in downstream ammonia and nitrous oxide emissions.
3. Implementation of integrated technologies for carbon control in the manure management chain can lead to methane emission reductions of >80% in 2030. This will provide a significant contribution to reducing the total GHG emissions as 80% corresponds to 2.4 Mt of CO_2-eq.
4. The effect on the climate impact through more resource efficient production and less waste in dairy production is estimated at approx. 24% in 2040, if milk yield per cow is increased from 9,500 to 14,500 kg. Approx. ¼ of this improvement is through improved management and precision livestock farming.
5. In 2030 development of biorefining of green and blue biomasses will reduce import of protein to the conventional livestock sector by 30%
6. By 2030, processing of food (feed, ingredients) has been converted (e.g., by implementation of novel technical solutions, electrification) to reduce CO_2 emissions by 70% and improve energy efficiency by 50% and water efficiency/reduction of water use by 30% compared to baseline 1990.
7. In 2030, 5% of the Danish animal protein production is from insects.

In 2050 animal-based food production will contribute towards a net-zero emission through:

- For the enteric methane from ruminants, it is realistic to anticipate emission reductions of >75%, and overall animal N-excretion can be reduced by 30%.
- For the manure management chain alone, it is realistic to anticipate methane emission reductions of >90% in 2050. Part of this may come from new methane capture technologies for livestock facilities, which will address both enteric and manure-derived methane.
- In 2050 almost complete circular production cycles are established. More than 75% of all feed is based on local sustainable production and recycling of nutrients from human waste and sludge is incorporated.
- Development of new products, fast methods, processing concepts and technologies, sensor and digital solutions and best practices to increase resource efficiency, competitiveness, and export of food, technology, and know-how, to achieve a firmly engrained mindset in the industry to facilitate the achievement of net-zero emissions in the food processing industry by 2050.
- In 2050 aquaculture and fish production is doubled in DK to around 100,000 tons per year.
- In 2050 insect protein is a natural food ingredient in Danish meals and a continuously growing part of the ingested animal protein.

Key activities and work streams

Cli	Env	Inn	Nat	Barr	
				BHR	Farmers' and consumers' perceptions as possibilities and barriers for reaching the climate goals for livestock farming
				CFG	Methane and ammonia reduction (Livestock)
				CFG	Capturing methane and ammonia (Buildings and systems)
				CFG	Circular perspectives
				FGR	Management and precision livestock farming
				CFR	Food product processes
				BFR	Alternative animal production systems

Effects on Climate (**Cli**), Environment (**Env**), Growth and Innovation (**Inn**), and Nature (**Nat**) from key activities within the track. Relative contribution is assessed by the colour intensity: darker is higher contribution than lighter, white is no contribution. In addition, barriers (**Barr**) are identified and include **B** Behaviour (Consumer); **C** Cost; **F** Financing; **G** Governance and Legislation; **H** Health; **R** Resistance to change in the sector.

Backtracking (gaps, challenges, and inflection points)

Some of the pathways of the sustainable transition of the animal sector towards the 2030 and 2050 goals are known but primarily in terms of knowledge on general measures and technologies. Transition towards climate smart animal production calls for research on the two main drivers: 1) Farmers' adaptation of new technologies and types of production; 2) Consumers demand for food with lower climate and environmental impact.

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› Enteric methane from rumen fermentation is the largest individual source that accounts for 35% of total GHG emissions from Danish agriculture, and more than 50% of the on-farm carbon footprint of milk. The technical solutions towards reducing enteric methane include four options: 1) Reduction of the production of hydrogen from microbial fermentation 2) Promotion of alternative and energetically favourable pathways for use of hydrogen 3) Inhibition of methanogenic archaea without compromising rumen fermentation and feed intake and 4) Identification and promotion of microbiomes that confer low methane emission. Solutions will typically be found in dietary interventions such as use of feed additives i.e., enzymes and probiotics. Genetic selection could offer a long-term reduction of methane emissions through either selecting for traits that have beneficial effects on emissions, and/or by identifying cows that are low emitters. However, this demands careful consideration of trade-offs and genetic constraints. While methane emissions by ruminants contribute the major share of GHG, monogastric animals also contribute. Feed is contributing to the major proportion of GHG footprint by chicken and pork meat, and reductions can be achieved through sustainable feedstuffs and development of feed supplements. Overall, selection for productivity – feed efficiency, growth rate and litter size in pigs, milk yield in cattle and reduced mortality are key factors, which all reduce the climate and nitrogen loads per unit of product produced while simultaneously improving animal welfare and economic performance.

In addition to reducing enteric methane emission directly from livestock, similar levels of reductions in climate footprint can be obtained by improved manure management and utilisation. An overall strategy for technology implementation and carbon accounting in the manure management chain needs to be developed with the aim of ensuring minimum methane formation during handling and storage as well as enhanced methane yield in the integrated biogas loop. Technologies include 1) Frequent or immediate slurry discharge combined with other technologies, 2) Treatment of residual pit slurry by additives or robot cleaning, 3) Close to elimination of methane emissions from external storages achieved by acidification or other additives, 4) Treatment of controlled ventilation exhaust from covered tanks. A whole-chain comprehensive documentation of relatively mature technologies is acutely needed to achieve the short-term goals. For reaching the long-term goal, new comprehensive manure management systems not only covering single farms should be considered. Biogas from digestion or co-digestion plays an increasingly important role in most manure management systems. Digested manure from biogas plants constitutes a specific challenge with respect to ammonia since there is a growing understanding that digestion of manure results in increased ammonia emissions from application. Reducing GHG-emissions through use of several technologies must not lead to loss of nutrient efficiency in the process, and technologies must not comprise the welfare of the animals. Optimisation of air treatment systems and integration with new ventilation systems has a potential for further emission reductions. Emerging agricultural air pollutants include volatile organic compounds (VOC) and sulphur compounds.

EU and national goals for more organic farming could make it more difficult to meet the goals for GHG reduction, since less solutions for emission abatement are available in organic farming. Livestock in organic farms use more space and hence more fouling area in some farms depending on management and layout. There is a great need to find alternative solutions that are acceptable under organic rules or a modification of rules.

Circular systems such as simple biorefining techniques based on traditional pressing, centrifugation, filtration, milling, air classification, sieving, as well as enzymatic treatment and fermentation techniques are available but still not widely used at farm level. The main challenge will be to further develop the techniques and combine these, to ensure high quality products in a sustainable, climatic friendly and bio-economical feasible way. To get the highest valuable compounds and fractions out of the processing, the crops for biorefining such as grasses, clover, alfalfa, cover crops, and seaweed, need to be optimised with respect to composition, cultivation, harvesting techniques and logistics in connection with the optimisation of the biorefining process. Algae, seaweed, salt and drought tolerant plants and microorganisms have also potential for producing feed ingredients, eventually by utilising or upgrading low value side streams (see track D: Biotechnology-based food production).

Documenting across the value chain using valid and reliable data in automated processes is essential to measure the impact of climate footprint reducing initiatives. Establishing a data sharing framework in agreement with all actors in the food production chain as well as establishing a shared data ›

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› platform are both important. Applying data and technology driven management systems i.e., drone technology, sensor technology, IoT technology for on-farm use and autonomous robots for farm use will be a part of precision livestock farming management in the future. Research and development of improved methods for use of big data with information about individual animals is needed to accurately modulate biological responses based on data in decision support tools.

The food product processing step contributes far less to the direct methane and GHG emission compared to livestock production. However, achieving a net-zero emission production is critical at all levels of the value chain. There is a need for technological solutions that will convert conventional animal food processors into resource optimised, sustainable and climate neutral operators. The value chains are complex, and a significant climate improvement requires rethinking of all links and connections in the whole value chain to be sure, that improvements in one link is not lost in a later link. Therefore, a post-harvest approach is crucial. The food industry partners face numerous challenges towards the conversion to become independent of the fossil fuels, optimize raw material utilisation and reduce water emissions and food waste. The potential exists to re-engineer the animal food industry by e.g., digital integration of sensor data to enable precision food processing, convert to electrical systems, introduce heat pump technology, and design recovery processes for optimal capture of water and side-stream resources.

Other animal productions include land-based fish production, which is presently associated with a high carbon footprint. However, fish production has a high potential to achieve a low carbon footprint compared to other animal productions, as fish have a high feed conversion ratio. Sea based production has a low carbon footprint, but a high emission of organics and nutrients, which must be addressed. Cultivation of mussel has proven efficient for N and P mitigation and food production purposes but is challenged by handling of large volumes for mitigation purposes and subsequent feed production as well as lack of technology for processing into commercial products. Insect production may be one link in mitigating some of the negative externalities from aquaculture production. For animal feed, a major challenge is that insects vary considerably in their content of macronutrients, especially fat, depending on the species, the life-stage of harvesting and production parameters. The immediate gaps for insects are in the areas of insect composition in regard to using insects as raw material in both feed and food products. Also, knowledge about insect production i.e., nutrient requirement, feeding, diseases and productions systems and GHG emissions is needed.

Track specific impact, timeline, and success criteria

The demand for significant national and sector specific reductions in national emissions is indisputable and due to the size of the livestock sector in Denmark, fulfilling these national goals seems unrealistic without significant reductions in emissions from our livestock systems. However, animals are also a part of the solutions for example because ruminants can use non-human edible side streams and fibrous foods to produce high-quality protein foods, thereby contributing to development of circular bioeconomy. Emission of ammonia from agriculture can be reduced by lowering animal nitrogen excretion, essential for reaching the strategic goal for the environment. In combination with improved utilisation of phosphorous, this will also lead to a reduction of pressures on aquatic and marine environments due to a reduced leaching of both phosphorus and nitrogen from manure.

An increase in perennial grassland crops, in nitrogen fixing crops (legumes), and a concurrent decrease in annual crops like grain and maize silage (with increased utilisation of cover crops) will reduce nitrate leaching, increase soil carbon sequestration, reduce use of pesticides with more than 90%, and if the forages are properly managed increase the number of pollinators. A further improvement due to an increased inclusion of marine biomass sources as feeds will reduce the amount of land required. Thereby more land will be available for purposes other than animal production, and overall biodiversity and recreational value can be increased on both national and global levels.

Food processing and food product activities will result in mapping and implementing technical solutions to recycle or reclaim water streams within the processing plant to improve branding possibilities and transparency of the food chains towards consumers and present and future employees, leading to increased competitiveness, job satisfaction and job retention. New process technologies will lead to reduced energy consumption. Moreover, this will result in an increase in yield and increased longevity of the products. This will ›

Track B Animal-based food production

› ensure a higher efficiency of raw materials and subsequent added value.

Strongholds and resources Reaching the overall climate goal for the animal-based food production sector will require a multidisciplinary and circular approach, with collaboration between researchers, product developers and industry people from a wide range of disciplines and professions. This will also be obtained through international networks and involvement in international projects and disseminations at conferences etc.

- The Danish livestock production has positioned itself as world leading in animal production efficiency, environmental management, and food science.
- Danish universities and knowledge institutions have a world leading position in animal science and manure management with a strong tradition of inter-disciplinary collaboration combining fundamental processes and implementable solutions.
- Research in green biorefinery has developed a strong knowledge base in Denmark with growing competencies on green protein as food ingredients and utilisation of side-streams for other purposes, as feed, biochar, building blocks chemicals, biomaterials, and bioenergy.
- Denmark has a long tradition in circular thinking as regards the utilization of side-streams from food and feed industries.
- Danish research on mussel and oyster cultivation has for decades provided new knowledge and technology.
- Strong competences in research on consumer behaviour, food demand, and agricultural economics.
- Danish consumers and companies are world known for the speed and readiness in adopting novel technologies and adapting to changes in framework conditions.
- The Danish farmers are well educated and are in general well prepared to adopt new technologies.

Risk management Achieving the results and impact from research related to livestock production is very dependent on access to state-of-the art facilities and further recruitment of highly skilled personnel. Use of feed additives that modulate the efficient rumen symbiosis may have adverse side-effects related to animal health and welfare and this has to be taken into account. There should be a strong focus throughout the area on avoiding adverse side-effects such as pollution and nutrient runoff to aquatic environments, mitigation measures that compromise animal welfare requirements or animal health and productivity. Production of protein and feed from green forages are proven and secure, while marine biomasses are more variable and may accumulate toxic compounds for animals and humans. Risk factors to be handled too are related to food security, when reusing waste and wastewater.

TRACK C **PLANT-BASED FOOD PRODUCTION**

Background The vision for plant-based food production is to contribute to the reduction of global GHG emissions by supporting the global transition towards healthier and more sustainable diets. There is strong scientific evidence that a more plant-based diet with less meat than the current Western diet has significantly lower GHG emissions and reduces the pressures on land use, water resources and biodiversity. More and more consumers are becoming aware of this and the global demand for plant-based food is increasing dramatically.

The market for plant-based food is expected to grow by 11.9% per year resulting in a total global market value of 455 billion DKK in 2027. If Denmark gets a share of the global market for plant-based food between 1% and 3%, this will correspond to a market value of between 4.5 and 13.5 billion DKK and the creation of between 9,000 and 27,000 new jobs in the food sector. It is estimated that this would require an increase in food crops from 300,000 to 600,000 ha by 2030, including between 100,000 and 150,000 ha protein-rich crops, as well as an optimisation of resource use efficiencies throughout the food value chain.

If we use these protein-rich crops for the manufacturing of gently processed, nutritious and tasty plant-based food products of high quality for both domestic use and export, they could replace the consumption of between 325,000 and 515,000 t meat (40% beef, 40% pork and 20% chicken). Based on the average European and global emission and land use factors provided by the World Resources Institute (WRI, 2019), this would reduce the global area required for producing feed by between 0.8 and 4.7 million hectares and ›

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reduce global GHG emissions by between 5.2 and 12.6 Mt CO_2-eq. by 2030, depending on the area allocated for pulses, the degree of processing, and the relative trade to different export markets. Besides contributing to reducing the climate impact of the global food system, the lower area required for feed will contribute significantly to improve water resources and biodiversity.

In order to fulfil the vision for plant-based food production we need to i) revitalise the Danish cooperative movement, establish multi-stakeholder collaboration between all relevant actors and strengthen the development of the plant-based food value chain from farm to fork; ii) link breeding and propagation of a diverse range of existing crops, novel crops and newly domesticated plant species with knowledge and analysis of food quality parameters (nutritional, functional and sensory characteristics) to optimize the raw material for good food quality; iii) develop resource use efficient management practices for conventional, organic and controlled environment agriculture (CEA), including vertical farming, and using plant biologicals and bio-based fertilisers to replace chemically synthesised pesticides, growth regulators and conventional fertilisers; iv) combine food crop production with low-density livestock production in regenerative and economically viable farming systems featuring perennial crops, intercropping, and agroforestry with high potential for carbon sequestration and provision of other ecosystem services; v) apply upcycling and recycling to upgrade feed to food by producing food ingredients for direct human consumption, and ensure upcycling of side-streams for feed and other purposes, while also integrating the production of bioenergy to minimise waste; vi) apply AI and robotics for developing autonomous fossil-free robots and remote sensing that can effectively perform a range of operations on high-value crops, including primary, post-harvest and food processing operations; vii) develop new sustainable and gentle processing of raw materials for making high-quality and tasty plant-based food products that can cover all nutritional needs, meet consumer preferences and ensure food safety and convenience; viii) trigger a large-scale consumer dietary shift by applying a holistic approach to behaviour change, exploiting the full gastronomic potential, and making the sustainable choice the easy choice; ix) develop robust methods for assessing the environmental, social, and economic impacts of more plant-based food production and consumption for the global, national, corporate, farm and product level; x) identify, test and scale viable transition pathways for overcoming existing barriers by building mutual trust and sharing knowledge across the value chain; xi) investigate and exploit the potential of private regulatory schemes and scaling up innovative niche public policy initiatives with transition potential at the national level to become transition drivers; xii) explore the options for transforming the Common Agricultural Policy (CAP) post-2030 to a sustainable Common Food Policy (CFP) assisting the transformation and maintenance of sustainable farming, processing, distribution and consumption and xiii) develop, test and scale business models that competitively, more sustainably, and resource efficiently, can address barriers related to plant-based food production and consumer requirements, in order to achieve maximum impact related to both environment and international business success, and to form the basis for a clear financing strategy.

Key activities and work streams

Cli	Env	Inn	Nat	Barr	
				BFLR	Collaboration and value chains
				BG	New and improved traditional breeding and propagation technologies
				FG	Plant biologicals
				CF	AI, robotics, remote sensing
				BR	New food crops and farming systems
				BFGL	Upcycling and recycling
				CFHL	Sustainable value-added processing of raw materials
				BGHL	High quality plant-based food products
				BCGH	Consumers and dietary change
				CFGR	Drivers and measures

Effects on Climate (**Cli**), Environment (**Env**), Growth and Innovation (**Inn**), and Nature (**Nat**) from key activities within the track. Relative contribution is assessed by the colour intensity: darker is higher contribution than lighter, white is no contribution. In addition, barriers (**Barr**) are identified and include **B** Behaviour (Consumer); **C** Cost; **F** Financing; **G** Governance and Legislation; **H** Health; **L** Logistics; **R** Resistance to change in the sector.

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Backtracking (gaps, challenges, and inflection points)
Current challenges and gaps within the plant-based food value chain are: i) breeding and propagation of a wide range of existing and potential food crops not targeted for optimising their nutritional, functional and sensory characteristics; ii) crop cultivation and management practices not optimised for resource use of efficient food crop production in stockless and low-intensity livestock faming systems, iii) plant biologicals, AI, robotics and remote sensing not sufficiently developed and implemented for making it possible to maintain or increase yield while phasing out the use of pesticides, and reduce water and energy consumption during processing; iv) lack of collaboration and weak distribution links, especially between farmers and food manufacturers; v) lack of on-farm or local facilities for storage, pre-treatment and processing of crops and raw materials; vi) no large scale pilot sites/commercial production facilities for upscaling the manufacturing of plant-based food products; vii) lack of knowledge on how to solve solubility, digestibility, shelf life and nutritional challenges in plant-based food products that are convenient and affordable for the main part of consumers; viii) insufficient documentation and certification of food safety, traceability, liability, life cycle analysis and sustainability assessment throughout the value chain from farm to fork; ix) inadequate utilization of raw materials and exploitation of residues/by-products for upcycling and recycling; x) nutrition policies, dietary guidelines and information campaigns not efficient for achieving widespread dietary change; xi) limited knowledge on how to overcome the cultural, behavioural, structural and institutional barriers for the transition towards a more plant-based food system; xii) lack of demand-side policies, governance arrangements and green public procurement for promoting more plant-based food production and consumption, and xiii) difficulty in attracting both seed and venture capital for food industry innovation, including financing of research and development, prototyping, testing and initial production.

There is a present need for increased private-public financing towards research, innovation, development, and implementation to enable the Danish society to overcome the barriers and fulfil its potential to become world-leading in fast-growing plant-based food value chains. Plant-based food production and its subareas lie between TRL 1 to 3 and SRL 2 to 3 at present and have the capability to surpass TRL 3-4 before 2025. It is expected that in 2030 all subareas will be between TRL and SRL 7-9.

Track specific impact, timeline, and success criteria
For each of the years 2025, 2030 and 2050 we have described 3 overarching goals for each of the ten key activities and workstreams listed above, as well as for three additional key activities and workstreams focusing on addressing barriers, providing financing, and assessing impacts. Furthermore, we have listed the related key measures and activities in the very near future.

With targeted development of the plant-based food value chain and strengthening of the existing and emerging research and innovation environments we will be able to increase the area of food crops from 300,000 ha to 600,000 ha in 2030, including between 100,000 and 150,000 ha with protein-rich crops. By applying new breeding technologies, optimizing management practices, improving farming systems, reducing waste, upcycling side streams, and applying plant biologicals, AI, robotics, and remote sensing we will be able to reduce the use of pesticides by 50%, reverse the decline of pollinators and improve water quality, while at the same time increasing crop production efficiency by 10% by 2030. By developing a range of unprocessed, gently processed, and fermented, nutritious, and tasty plant-based food products made from sustainable Danish food crops and contributing to facilitating a consumer behaviour change, we will be able to replace global consumption of between 325,000 and 515,000 t meat. Further, it will make it possible for Danish food sector companies to build on existing strongholds in combination with famous gastronomic environments in Denmark to scale production of value-added plant-based food products for export. Coupled with addressing the structural and institutional barriers and providing the necessary regulatory and financial drivers and incentives for a transition towards a more plant-based food system, this will enable Denmark to contribute to a reduction of global GHG emissions between 5.2 and 12.6 Mt CO_2-eq. by 2030, including between 0.5 and 1.1 Mt CO_2-eq. resulting from increasing the efficiency of food crop production. Furthermore, a sustainable and healthy diet will give an overall health effect of 26.968 DALY (disability adjusted life years) and a corresponding health economic cost reduction of between 9.9 and 11.9 billion DKK per year.

The overall goals to reach by 2025 are: i) identify and co-create new actionable knowledge on selected transition pathways

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› and value chains where Denmark has potential as a future stronghold for plant-based food production; ii) build transdisciplinary research capacities that span the entire food system and leverage this research for smart planning and management of food system transition; iii) bring together key actors to build mutual trust, shared knowledge on how to overcome barriers, and shared understandings of smart policy mixes.

The overall goals to reach by 2030 are: i) iteratively explore new barriers and potentials given how the interplay of market designs, social norm changes, and regulatory drivers develop at local, national, EU, and global levels; ii) consolidate and spur growing domestic demand for plant-based proteins, as well as Danish companies' larger-than-average share of the growing international market; iii) further the contribution to national climate and biodiversity targets by verifying direct emission reductions and sequestration from changing land-use (e.g., forests).

The overall goals to reach by 2050 are: i) incentivise, manage, and monitor transition to a food system where most protein for human consumption is sourced from plants, and most agriculture relies on plant-based production; ii) monitor and iteratively build capacity across the food system to turn Danish agriculture into a source of net zero or, where possible, net negative emissions; iii) continuously improve adaptive transition capacities through processes of reflexive evaluation, monitoring, and learning among all societal stakeholders, nationally and internationally.

Related key measures and activities in the very near future:

- Establish selected and cross-cutting stakeholder consortia, corresponding to the value chains identified as holding the greatest potentials for plant-based food production in Denmark.
- Set up technology testbeds and innovation incubators to experiment while at the same time generating new knowledge on food system-wide economic, social, and institutional barriers.
- Facilitate on-going policy dialogues, helping to locate and soften regulatory barriers, as well as broad-based public dialogues to enable social license and legitimacy for policy shifts.
- Make transdisciplinary research central to collective learning loops for accelerated transition, continuously monitoring and adjusting according to climate and biodiversity goals.
- Address social sustainability in all activities, i.e., how food system transition will entail both winners and losers and how the latter may be fairly compensated and assisted.

Strongholds and resource overview By investing in research, innovation and implementation of the plant-based food value chain, Denmark has an enormous potential to quickly assume a leading position with an advanced agricultural sector and a strong ecosystem of ingredient companies to provide cultures and equipment suppliers, suppliers of analytical tools, and large number food producers. We are well positioned due to our significant experience in high-efficiency agricultural production and our strong traditions and institutions in agriculture, nutrition, food research and innovation. This enables us to support, foster, and accelerate new plant-based value chains that are today in an early, emerging stage. Denmark has research strongholds needed to support the strategic climate goals and position us as one of the leading exporters of plant-based ingredients, such as food processing, protein chemistry, process analytical technology, process design, food safety, energy and unit operations, environment, and water technologies. Denmark has strong competences in research on consumer behaviour, food consumption and demand, as well as food regulation and governance. Denmark is in a unique position due to its 2021 dietary guidelines promoting a plant-rich diet that addresses both health and sustainability. We have the potential for a food system transition, but we need to do transdisciplinary research to be able to foster an accelerated transition in the coming years. So far, the funding landscape has not prioritised plant-based food, and this needs to change to mitigate the risk of Denmark losing this big commercial opportunity and strengthen opportunities related to plant-based food production as a new Danish business stronghold. Research and development build and expand on existing strongholds and emerging areas such as: new breeding and propagation technologies, new food crops and farming systems, plant biologicals and AI, robotics, and remote sensing. As well expand already established Danish strongholds such as upcycling and recycling, sustainable processing of raw materials and novel food products further into the plant-based food sector.

The proposed activities will involve the entire research, innovation and implementation ecosystem: Universities, GTS, and the entire value chain in the private sector: farmers ›

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› and their suppliers, the food industry and their suppliers, the retail sector and consumers and the stakeholder organisations for farmers, businesses, employees, consumers and citizens, horticulturalist organisations, advisory services, breeding companies, energy suppliers, recycling and waste contractors and NGOs focusing on agriculture, food, climate and environment.

Risk management Reaching TRL 3 and beyond in 2025 will be a long shot if impact assessment is a prerequisite for commissioning of technologies, regulation etc. The paradox is that we cannot wait to develop technologies but do not have the ability to assess the complete impact before the technologies are further developed. Therefore, solutions should be based on current models until we have developed new hybrid LCAs with multiple sustainability criteria.

Consumer acceptance and demand as well as existing EU legislation might slow down implementation of new breeding and propagation technologies, plant biologicals and upcycling & recycling. To mitigate risks on environment, climate and biodiversity, the private and public policies to transform agricultural production to being more plant-based should be evaluated: increased consumption of plant-based food, including legumes, and a concomitant lower intake of animal protein need to be carefully investigated for potential risks.

Business risks are a lack of scalability of innovative food producers, a lack of innovation in processing equipment industry, and inertia from large retailers and food producers. The international as well as the knowledge-based implementation system are key to mitigating risks.

TRACK D BIOTECHNOLOGY-BASED FOOD PRODUCTION AND ALTERNATIVE PROTEIN SOURCES

Background The vision of track D is to reduce the harmful impacts of food production on climate, environment, and biodiversity and to lower the land use required for feeding the growing global human population.

This will be enabled via i) biorefining for feed and food, ii) cellular agriculture, iii) alternative proteins and side-stream upgrade, iv) new functional feed additives and biologicals, and v) food processing technology to reach circularity. These five enablers represent vast and growing value pools where Danish industry has significant strongholds and hence a great potential for accelerating sustainable solutions to the global challenge of increasing the production of safe, tasty, and healthy food and not least, a tremendous potential for growth.

The challenge Reaching climate neutrality by 2050 is particularly challenging for the food sector. The rapidly increasing world population towards 2050 in combination with increased buying power and urbanization will create a surge in the global demand for nutritious and tasty foods, and one of the major global challenges is how to achieve adequate production of high-quality functional protein for the growing population while simultaneously reducing the adverse impact from food production on climate, environment, biodiversity, and land use. The above enablers are characterised by different challenges that in turn will be addressed in and across several work streams.

Importing millions of tons of particularly soy undercuts farming standards in the European Union, destroys tropical forests and biodiversity and renders Denmark and the EU as exporters of adverse climate, environment, and biodiversity impact. Imported feed proteins must be replaced by locally sourced proteins to reduce the deforestation and biodiversity impact of European animal production. Developing green biorefineries and upgrading of side-streams from the bioeconomy are key workstreams to address this challenge.

Since meat production is one of the more significant contributors to GHG emissions we need to not only find new sustainable ways to produce our traditional high-quality foods and ingredients, but also to utilise our existing resources more efficiently and include alternative sustainable protein sources. There is no single solution to combat the challenge, and to enable this transition it is necessary to develop a plethora of complementary sustainable alternatives and engage in a broad range of innovations in a series of work streams elaborated below.

Greenhouse gasses are consumed and produced by the associated microorganisms and targeted stimulation/inhibition of these will reduce emission of GHGs. Improved animal health and enhanced feed conversion rates, too, contributes to reducing the climate footprint of animal production and replacement of antibiotics. Significant knowledge gaps also include soil and plant microbiomes, novel feed supplements and biologicals to replace synthetic chemical plant protection agents. We need to integrate and model the vast amount of data produced in time and space, to optimize methods for high-throughput data generation and AI assisted analyses thereof. ›

Track D Biotechnology-based food production and alternative protein sources

Key activities and work streams

Each work stream contributes to different Innomission targets and are characterised by several key barriers.

Cli	Env	Inn	Nat	Barr	
				BCG/H	Biorefining for feed and food
				BCFG/R	Cellular agriculture – stem cell meat, microalgae, precision fermentation
				CFR	Microbiome engineering in agriculture, aquaculture, and bioprocesses
				BCHLR	Microbial and enzymatic upgrade and value-added products from side streams
				BCHR	Alternative proteins and other food ingredients
				CR	Optimising existing processes for resource efficiency

Effects on Climate (**Cli**), Environment (**Env**), Growth and Innovation (**Inn**), and Nature (**Nat**) from key activities with the track. Relative contribution is assessed by the colour intensity: darker is higher contribution than lighter, white is no contribution. In addition, barriers (**Barr**) are identified and include **B** Behaviour (Consumer); **C** Cost; **F** Financing; **G** Governance and Legislation; **H** Health; **L** Logistics; **R** Resistance to change in the sector.

Backtracking (gaps, challenges, and inflection points)

BIOREFINING FOR FEED AND FOOD

Two demonstration plants for green leaf proteins are in operation from mid-2021, yet processing steps must be optimised for efficient and cost-effective production of food and feed ingredients. Food products must be Novel Food compliant and nutrition, toxicity and allergenicity assessments should be integrated from TRL4-5 onwards. The key inflection points for national scale implementation for green leaf biorefining will be achieved when i) the feed fraction is competitive with imported soy in non-organic farming and ii) the food fraction achieves Novel Food authorization, iii) functional properties have been demonstrated in food matrices, and iv) consumer acceptance at SRL9. We expect inflection point for the feed fraction to be achieved by 2023-25; for the food fraction by 2025-27, and 2027-29 for pulses.

CELLULAR AGRICULTURE – STEM CELL MEAT, MICROALGAE, PRECISION FERMENTATION

Substantial research and innovation are required to accelerate the TRL progression including to i) identify the optimal cells and process design for cultured meat and algae and establish nutritional quality, ii) identify and engineer the optimal microbial cell/combinations for functional food components, iii) fermentation, optimisation of yield, platform strains, engineering tools, post-translational modifications, harvesting and protein extraction, iv) cost-efficient, low emission feedstocks and consumer-acceptable ingredients for the culturing/fermentation media, v) evaluate food safety, functionality and nutritional quality compared to conventional products, and vi) adhere to Novel Food/GMO regulations on nutritional quality (compared to conventional products), toxicity (chemical, microbiological) and allergenicity. Key inflection points are at proof of concept at TRL 3-4, proof of scalability and demonstration in pilot plants at TRL 6-7; Novel Food authorisation, and consumer acceptance in SRL 9. Implementation at industrial scale is expected to take off in ~2030.

MICROBIOME ENGINEERING IN AGRICULTURE, AQUACULTURE, AND BIOPROCESSES

Microbiome engineering faces common as well as distinct sets of gaps related to plant, soil and gut, the latter representing disparate digestive systems in fish, monogastrics and ruminants. To use microbiome engineering in a predictable manner, we must i) develop modelling approaches that enable prediction of microbiome functionality, ii) develop better precision tools for selective modulation or knock-out of individual microbial species or strains, iii) develop sensor methodology for increased speed and accuracy, and iv) develop analytical tools to understand how microbiomes change after precision engineering. Key inflection points include a) validation of high throughput workflow (2025), b) establishment of a molecular biology toolbox based on nanobody technology for precision engineering of key strains (2030), and c) full functionality of microbiomes in any niche can be analyzed within a day and targeted engineering modelled and implemented within a week (2050).

MICROBIAL AND ENZYMATIC UPGRADE AND VALUE-ADDED PRODUCTS FROM SIDE STREAMS

This work stream develops technologies for enzymatic treatment and fermentation of food byproducts and waste

Track D Biotechnology-based food production and alternative protein sources

› to secure circularity in the food sector and valorisation of side-streams including challenges of i) side stream natural variability, short stability and for some streams, seasonality, ii) logistical solutions for collecting side-streams across the workstreams, iii) improved pre-treatment technologies for feedstocks, better enzyme cocktails, iv) microbial strains to improve quality and usability of side-streams by fermentation, v) optimisation of yield, strains, engineering tools, vi) harvesting and protein extraction and vii) development of safe, tasty and healthy foods. Understand the functional and organoleptic properties of ingredients in concert with each other. Key inflection points include a database on mapping and characterisation of waste streams (2023-25), biobanks with platform strains of bacteria, enzymes and fungi (2030) and toolboxes for precision engineering and AI assisted predictive microbiology models (2030) enabling fast and efficient product development pathways.

ALTERNATIVE PROTEINS AND OTHER FOOD INGREDIENTS

There is a huge potential for using the vast biodiversity of alternative species to provide novel sources of feed and food proteins and other ingredients from diverse biomasses such as bacteria, yeast and fungi, microalgae, green plant biomasses, insects, lower trophic aquaculture including bivalves, other invertebrates, seaweed, and new marine resources. Limited functionality of some alternative proteins can be solved by enabling functional food ingredients to ensure palatability and processability. Key inflection points include closing the knowledge gap on i) bioavailability of micro- and macronutrients, ii) techno-economic potential for extraction, stability, suitability for processing, iii) functionality including sensory properties and how this is linked to their structure, and interaction with other food ingredients, iv) nutrition value and safety established, v) processing steps for Novel Food compliance and vi) consumer acceptance. The timing of the inflection points varies widely between the biomasses and are linked to the above work stream on microbial and enzymatic technologies.

OPTIMISING EXISTING PROCESSES FOR RESOURCE EFFICIENCY

Develop solutions to optimise existing food processing industries to secure higher conversion ratio per unit raw material with the input of less water and energy to attain optimised, sustainable and climate neutral operators in the food value chain providing healthy and nutritious foods. Key value inflection in energy use occurs i) when process integration between heating and cooling demands by direct heat recovery and heat pumping and by electrification and other technologies can substitute fossil fuel-based heating cost effectively, ii) when more radical technologies, e.g., ohmic heating, MVR technologies, microwave drying systems, IR, direct steam injection etc. reach parity with conventional technology on cost, quality, functionality, and safety of products. An inflection point is reached when R&D has progressed the understanding of the “right” water quality for cleaning purposes.

Track specific impact, timeline, and success criteria

The GHG emissions, land use and water consumption from cellular agriculture and alternative proteins are low compared with the equivalent animal-based production processes and the potential is even higher if agricultural and industrial side-streams are used as feedstock. Towards 2050 the feedstocks for the microbial fermentation processes can even be CO_2 and green hydrogen which could result in net negative GHG emission.

2025: Green biorefining for substitution of imported protein feed reaches proof-of-business and the commissioning of 5-10 commercial plants. Proof of concepts have been obtained and technology platforms in all work streams have progressed to enable acceleration of i) valorisation of waste streams and alternative protein sources together representing enormous biomass pools rich in protein, carbohydrate and other valuable nutrients, ii) commercial production of high-yield protein is established within bivalve, microalgae, seaweed, insects and micro-organisms, iii) Commercial insect-based feeds are gaining market shares, iv) bacterial protein production from biogas, CO_2/hydrogen developed, v) implementation of energy and water saving technologies. 5-10 new alternative ingredients and additives with global market potential are launched. Consumer acceptance of foods based on alternative proteins and side streams is growing.

2030: Green protein has displaced all imported soy protein in organic feed and 5% of conventional feed. Numerous novel feed and food ingredients products are launched. Feed is partially replaced by products generated from waste. Upscaled processes from side-streams are accelerating based on extensive development of technology platforms across work streams. Consumer behaviour, preferences, and acceptability ›

Track D Biotechnology-based food production and alternative protein sources

› with respect to new foods are well understood and gauged and engineering advances enable efficient product development with shortened time-to-market. Alternative protein sources constitute 10-20% of national consumption of protein products as included in a healthy, sustainable, and varied diet, including plant-based, from alternative protein sources or side streams. The food industry is exceeding closing the gap on circularity. Processing of food has reduced CO_2 emissions by 70%, improved energy efficiency by 50% and water efficiency/reduction of water use by 30%.

2050: Biotechnology-based solutions, alternative protein sources and advances in processing technology has de-linked food production from accelerated climate change, environmental degradation, deforestation, loss of biodiversity and excessive land use for food and feed production. Plant and cell-based protein is well established in global value chains. Danish industry has spearheaded significant parts of the transition and strengthened its market position.

Danish strongholds relevant to the challenge The Danish position is unique in the sense that universities and industries possess many of the broad spectra of research competences required for research and development in sustainable food production processes. These include cross-disciplinary research in biorefining, cellular agriculture, resource efficient food processes, enzymatic hydrolysis, separation methods, fermentation, cell factories and microbiome engineering, alternative protein sources and scientific disciplines needed to investigate the uses of these newly developed proteins as well as their limitations, including LCA, functionality, rheology, sensory, nutritional and health properties.

In Denmark we also have essential competences when Novel food/GMO approval processes, including food safety assessments, consumer acceptance, legislation and product labelling are required.

Denmark is endowed with industrial strongholds in life science, in food and feed ingredients and in biologicals. The Danish life science sector is a driver of growth and exhibited a 5.2 times higher growth rate than the Danish industry at large over the eight years leading up to 2017. Danish life science employs 50,000 people, of which many are in R&D and contributes with 140 BDKK in export in 2019. A substantial part of the industry is fermentation based. The Danish food and feed ingredients industry turns over 40 BDKK annually, employs 10,000 and creates more than 60% more value per employee than an average worker in Denmark. The food and feed ingredients industry has a long tradition for utilising and optimising the side streams. Denmark has a significant reputation within gastronomy which can pave the way for implementation of new functional ingredients. Finally, Denmark is host to world leading companies and has attracted foreign direct investments in the growing market of biologicals. All the above strongholds are characterised by companies that invest significantly in R&D and with extensive collaboration with the universities. Denmark is thus well positioned to develop novel biotechnology-based solutions for the green transition and for reducing the climate and environmental footprints of food production.

Risk management Many new food components and ingredients fall under the novel foods legislation requiring time and cost for approval and uptake of the technological solutions by industry, and compliance with the EFSA Novel Food Authorisation should be an integrated part of product development from TRL4/5 to optimise product quality, time-to-market, and parity with conventional food products. Genetic engineering should be performed with as few genetic changes as possible, and ingredients must be purified leaving no traces of the GMO or inactivation of microorganisms. A mindset change around GMO will be required.

The strong trend in growing consumer demand for plant-based and novel climate friendly foods must be leveraged and underpinned by the development of safe, nutritious, tasty, and healthy food products. Consumer acceptance of novel foods should be carefully tested before implementation to avoid negative experiences and adverse market effects. Cost structures of new feedstocks and processes may be prohibitive for commercial exploitation without incentives and/or the risks makes business models not attractive. To increase the interest and confidence of industry it is necessary to start with the low hanging fruits and develop new exciting and tasty foods to interest the consumers.

The key societal risk is underinvestment and too little and too late regulatory initiatives to incentivise and accelerate investments in research, development, and innovation for climate neutral food production that in turn will improve the state of the global environment and biodiversity.

CROSSCUTTING ASPECTS

Background Technologies and land use options already exist that can take parts of the Danish agri-food system a step further towards the 2030 and 2050 goals on climate, biodiversity, and nutrients. However, there are many barriers towards implementation. As this roadmap and related research and development efforts unfold, even more technological pathways will open, further calling for new and effective implementation pathways and incentives to drive the transformations. The vision here is for Denmark to become a world leader in knowledge driven sustainable transformation of the agri-food system, through governance systems that fast-track effective technical innovations into optimal implementation in the landscape and along all value chains. The development of incentives to support implementation of existing and novel technologies is pursued through three work streams: i) Constructing the most detailed, consistent transparent and well documented GHG accounting system possible allowing us to assess effects and flows to be calculated equally at instrument levels, at farm level, as well as at national level and product level. ii) Developing a data-driven agri-food system, which intelligently integrates all forms of digital data, be they geo-referenced images, sensor-based data services etc., uses unified semantic object descriptions, efficient data transmissions and transformation. iii) Developing innovative, data driven documentation and incentive systems to enable optimal coordination of climate mitigation actions along with measures for environmental and biodiversity protection across farmers and the food producing industries and to stimulate consumer-citizens to drive transition through demand. Denmark is uniquely positioned to succeed in pursuing the vision. Danish citizens and companies are world known for the speed and adeptness with which they adopt novel technologies, provided suitable incentives, and the Danish agri-food system is among the world's most technologically advanced and highly integrated within the sustainability policy context.

Gaps and challenges All work streams address several current gaps and challenges to further a cost-effective sustainable transition of the agri-food system. We highlight a few central ones:

- National climate accounts generally contain few options to include variations in effects of new or existing technologies that reduce GHG emissions from the agri-food system. For example, N_2O emissions are estimated relative to all nitrogen inputs, irrespective of measures in place that reduce emissions. There is a great need to develop and document differentiated emission factors and models.
- It is a challenge to document farm level management and activity data, and to establish a data flow from farm accounts to product accounts across food companies and others. Implementing coherent and methodologically aligned GHG accounts presents a significant coordination challenge.
- There is a lack of purpose driven data collection and representation and efficient data sharing across the agri-food system, despite an increasing use and generation of geospatial data, sensor, and activity surveillance data. This hampers advanced use of data for pursuing climate, environmental and biodiversity goals cost effectively.
- There is a need to develop systems for enabling quality assurance of relevant data collected along the value chains of the agri-food system and the public sector, and to implement secure sharing systems and standards.
- There is a major lack of instruments and incentive structures, be they public-private or private-private, that – on a solid and consistent data basis – can induce farmers and industries to innovate, develop and adopt new climate and environmental mitigation measures effectively.
- Inducing behavioural change among consumer-citizens' dietary habits is exceedingly difficult, and lasting change requires that all factors (information, social norms, choice context design, product appeal, etc.) are addressed to trigger widespread and up-scaled behavioural change. This requires holistic approaches and food system wide collaboration and action.

Key activities in and across work streams The three work streams described here cut across the four other tracks of this roadmap, i.e., the land use and management, the animal-based, the plant-based and the biotech and protein tracks. Their work streams constitute a coherent system enabling good governance and self-governance for the agri-food system to undergo a sustainable green transition. The work stream on developing a consistent and credible GHG emission accounting system constitute an important basis for several aspects of the work stream focused on innovative regulatory and incentive systems, and the simultaneous development of ›

› both would be instrumental for speeding up implementation of existing and new measures and technologies. Thus, these activities need immediate attention, see the timeline below. The full vision includes an integration of both work streams with a thorough digitalization of the entire agri-food system, the core of which needs attention soon, but for which the full potentials will be harvested beyond 2030.

KEY ACTIVITIES IN THE WORK STREAM ON IMPROVED GHG EMISSION ACCOUNTING SYSTEMS

- To develop a methodology and database for GHG accounts for agricultural holdings, with flows and inventories mapped according to territorial and LCA principles, which can provide data for the national GHG and for product accounts. Data from production management tools may be a source of detailed data at field and herd level.
- To develop and document differentiated emission factors for both nitrous oxide and methane, so that mitigation measures and technologies that affect emissions can be reflected in the GHG accounts, and to develop novel measurement methods and programs to verify emission calculations and estimates as well as accountings.
- To develop the necessary database and estimation methods for soils, trees, and perennial biomass in the landscape to allow a scientifically sound integration of their carbon storage into greenhouse gas accounts, enabling new sequestration measures at farm and national level.
- Initiate a coordinated effort across the agri-food system and with support from research to develop and operate rational systems to prepare fair product accounts in a Danish context that complies with international, recognised standards and guidelines. The GHG accounts should be included in an overall assessment of environmental impacts and sustainability at farm, product, national and food chain levels.
- Foster innovation in the preparation of product accounts in accordance with LCA principles and their interpretation. Establish open data structures and the possibility of reusing data in different calculation models in support of guidelines for accounting depending on which questions are to be answered.
- Develop methodology and database for biomass and nutrient flows that are integrated into GHG accounts at all levels. The nutrient accounting ensures mass balance and high data quality.
- Explore the potentials for GHG accounting to be integrated with other environmental goals such as water quality (N, P), ammonia losses, pesticide use, biodiversity, and animal welfare. Including cost considerations, this may allow for decision-making tools at farm level regarding the selection of mitigation measures and changes in land use and production systems to achieve societal objectives.

KEY ACTIVITIES IN THE WORK STREAM DEVELOPING A DATA-DRIVEN AGRI-FOOD SYSTEM

- To underpin governance and industry development with advanced data capture, analyses, and digital tools, a first mapping of current data capture structures and data losses is needed; covering geo-referenced field data, production process data, logistics and retail data.
- To evaluate potential and development needs, case studies on specific parts of the chains are undertaken using Digital Twins for selected cases (products, companies, processes) to demonstrate the benefits of advanced digital infrastructures and inform of development and upscaling challenges. Data focus on GHG emissions, environmental impacts, land use etc.
- To identify key transformations of products/foods in the chain from field to consumption to generate data on food and process properties and impacts and waste and material streams as a basis for data-based representations of value chains.
- To implement digital resource flows, whereby the integration of circularity data and knowledge will enable interoperable and meaningful data exchanges manifested as apps and services. Provide a digital architecture for the value web and integration with established food domain data platforms for building resilient consumer-centred value chains.
- The long-term goal is to enable multi-directional data/knowledge flows across the agri-food value chains based on transparent and secure data collection and use.

KEY ACTIVITIES IN THE WORK STREAM ON REGULATION AND INCENTIVES FROM FARM TO CONSUMERS

- Setting aside carbon-rich agricultural soils, afforestation or use of land for biodiversity and renewable energy ›

›

production is of major significance. We propose fast-track research with experiments-at-scale to design cost effective instruments relying on competitive bidding among landowners and private intermediaries to resolve aggregation and transactions costs.
- Friction free coordination of efforts across farms and companies will allow them to profit from differences in installed technology, and ability to adapt with low marginal costs of abating GHG emissions. Researching and testing private-private market-based instruments e.g., with forms of tradable GHG credits allow companies to coordinate effort and reduce cost. Appropriate monitoring should support instrument implementation, e.g., the transparent GHG accounting presented above.
- Enhancing consumer demand for sustainable foods will require research into how information on product level GHG impacts, enhanced shopping contexts, education and the application of living labs and interventions studies can enhance and build consumers' willingness and ability to adapt their diets and food habits and change social norms on these.
- Building on advances in documented innovations within this roadmap, research institutions and the private sector jointly innovate instruments for sustainable financing, based on reduced environmental tax/cost burdens and risks creating real market value.
- The agri-food system is a globally competitive market and any regulatory instrument or policy targeting sustainability must be assessed in that context. This should be supported by novel partial sector and general equilibrium models that capture leakage of production, environmental and land use impacts globally, and enable assessment of rural development effects in Denmark.
- We explore the potentials for integration of the digitalised agri-food system with novel incentive systems, which may increase credibility of environmental impact gains, enhance transparency and enable enforcement in a transparent way.

Track specific impact, timeline, and success criteria
Establishing a transparent and detailed basis for GHG accounting at all levels from farm and product to national levels is urgent and starts from an already strong basis in the sector. Likewise, designing novel incentive systems and good documentation to support companies and consumers/citizens in the forthcoming sustainable transition is urgently called for to reap low hanging fruits and enable the agri-food system to benefit from existing and new technologies. Here, we start from a strong basis of collaboration between research, the private sector, and relevant agencies. For both work streams, early gains at high SRL are possible and targeted. Achieving the full vision of the data driven agri-food system will require long-term investments in infrastructure and procedures, and while the first steps must be taken now, the full benefits will come later. This path is reflected in the developments of SRL shown in the following table.

SRL	GHG accounting	Digitalisation	Incentives, documentation, regulation
1			
2		2021	
3			
4		2025	2021
5	2021		
6		2030	
7	2025		2025
8			
9	2030	2050	2025/30

Under the rough timeline shown in the table, several successes will be achieved at the different inflection points indicated and implied in the table. We highlight only a few across the three work streams here.

One of the first low hanging fruits is a faster and more cost-effective implementation of the land use changes in agriculture that both the agricultural and nature conservation NGOs pursue, but policy implementation is lagging and potentially too burdensome for the sector. We hope to set this on track at full-scale speed by 2025 already, saving both Mt of CO_2 emissions and billions of DKK. As more transparent and high quality GHG accounting systems are developed, they will form the basis for better decision making along the agri-food

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Crosscutting aspects

› systems value chains, enabled by concurrent development of public-private or private-private incentive structures that enable better coordination of impact efforts along the chain and across actors. Mapping data streams and harvesting and enhancing the basis for data sharing are early steps on the path to a fully digitalized infrastructure of the agri-food system, and case studies will outline potential benefits of upscaling. However, it will take longer before structures are fully in place to harvest at full scale the right data and share them in secure and validated ways for better governance and business performance. These benefits will not arise before 2030 and later. Some of the more advanced governance gains, e.g., a fully validated assessment of policy impacts at local and global levels, including leakage of not only jobs and business potential, but also climate and other environmental effects, will not be ready before 2030.

The potential impact of the activities under this cross-cutting theme can of course not be seen independently from the qualities of the technologies and behaviours they incentivise. The ambition is for Denmark to become a world leader in implementation, i.e., getting from technical innovation to sustainable transformation of the agri-food system, through improved data driven governance. In its recent report the Danish Economic Council shows that the difference for the overall Danish economy between less coordinated and well-coordinated governance represents approx. 10-15 billion DKK/year, and approx. 5,000-10,000 jobs. The effects of this research effort will be lower of course, as it targets mainly the agri-food industry, and may not realize the full theoretical potential. However, the agri-food sector is a substantial part of the challenge still facing society in terms of mitigation, and most environmental impacts harvested as co-benefits relate to this sector. If fully successful, we expect an impact measured in single-digit billion DKK savings, corresponding to thousands of jobs, for facilitating GHG reductions of approx. 8 and 17 Mt CO_2eq annually by 2030 and 2050, respectively. Note that this is an impact from coupling governance with the technologies and decision changes they incentivise across all tracks in this roadmap.

FIRST YEAR KEY WORKSTREAMS AND ACTIVITIES

The key workstreams and activities will differ between different partnerships depending on the tracks described in this roadmap. However, there are some common key activities that need to be undertaken in the first year of all partnerships, as listed in the table below.

Partnerships, organisation, agreements	Develop the organisational frame for the partnerships and the legal agreements within the main partnership and for affiliated partners.
Barriers management	Develop the framework for analysing barriers for the implementation of measures, as well as strategies for overcoming barriers.
Living labs and demonstration farms	Develop a network of living labs with associated measurements and data infrastructures. The living labs will cover farming systems e.g., conventional and organic farming, conservation agriculture, vertical farming and pilot plants e.g., biorefinery, pyrolysis and fermentation plants.
GHG testing and approval infrastructure	Set up a physical and logistical infrastructure for testing and approving technologies for GHG mitigation in agriculture.
GHG – Data infrastructure	Design of GHG data infrastructure for supporting accounting of mitigation measures at farm, food, and national scales.
Experimental planning	Planning and setup of experimental activities.
Financial overview and analyses	Analysis of investment needed and innovative funding pathways.

MILESTONES, TIMELINE AND SUCCESS CRITERIA

The background work on this roadmap advises a vast number of milestones, more than 100 concrete goals and more than 100 activities and measures, which cannot all be listed in a common timeline. As the roadmap covers land use and climate and environment friendly food and agriculture broadly, it is suggested to choose a model assessing progress biannually and using the assessments as go/no-go points for next steps and as part of refining and updating the roadmap.

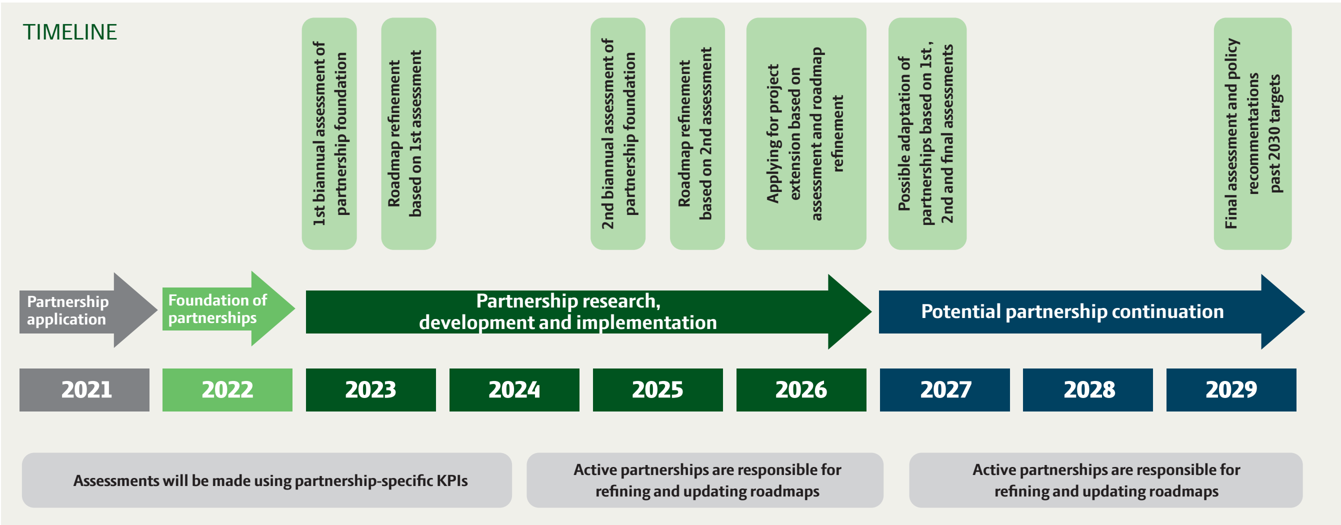
Progress would be measured in terms of assessment of roll-out of activities and in terms of assessment of these activities' ability to create traction towards the specified goals and anticipated impacts.

It is suggested that the roadmap is refined and updated as result of these assessments. Furthermore, it is expected that some of the assessments will function as go/no-go points for certain activities and in case of a no-go be starting point for alternate routes. By 2026 these assessments should also be part of assessing and applying for an extension of the partnerships. The roadmap lists activities, goals and expected impact at an overarching level. It is expected that it will be the responsibility of each partnership to assess and report on its activities and progress against the roadmap goals and expected impact. In 2023 we suggest to only assess the foundation of the partnerships against the roadmap, as it will be too soon to assess traction towards goals and impact.

Success criteria Main success criteria through all partnerships will be if the partnership activities are on track to mitigate key 2030 challenges: 1) reducing GHG emissions with 70% by 2030, 2) reducing methane and nitrous oxide emissions from livestock and cropland production, 3) 24% reduction of ammonia emissions by 2030, 4) reducing the use of pesticides by 50% by 2030, 5) turning 30% of land into protected areas and create more biodiversity, 6) Reverse the decline of pollinators, and 7) plant 3 billion trees. All this while simultanously increasing food production, revenue and jobs in the agriculture and food sector.

Traction should be assessed against ability to meet the foreseen development in SRL and TRL, as well as how well activities of the partnership are on track to contribute to 2030 and 2050 goals regarding climate, environment, biodiversity, and job creation described in the roadmap.

Foundation and activity assessment should include assessment of involvement of stakeholders/partners, attraction of financing, if all activities have been established and if the activity is on track in terms of Key Performance Indicators (KPIs). Specific KPIs are expected to be established by partnership applicants as part of "Phase 2 call for Innomission-partnerships".



Roadmap management In addition to the management structure with a Managing Partner of the public and private partnerships and boards for each partnership, international assessment boards are established to review the progress of the partnerships and to recommend strategic prioritisation to the boards.

Relations to other roadmaps and missions Climate and environment friendly agriculture and food production is one of four R&D missions considered by the Danish Government as key to reaching the goals of 70% reduction in GHG emissions in Denmark by 2030, and net-zero emissions by 2050. The roadmaps for the four missions are interlinked. For the climate and environment friendly agriculture and food production roadmap, this is particularly evident within › pyrolysis for carbon capture and storage of biochar, in which the innovation pathway has bearings on innovations in Innomission 1 (Carbon Capture, Utilisation and Storage) and notably in Innomission 2 (Power to X), possibly upgrading the biooil and syngas fractions from pyrolysis to carbon-based fuels. The potential for production of biochar for offsetting emissions depends on the PtX pathway chosen, but we estimate the need for offsetting using biochar in the order of 2 Mt CO_2 annually by 2030. There may further be interlinkages to Innomission 4 (Circular economy with a focus on plastics and textiles) as the fibre fraction from biorefining may be useful in non-food sectors covered by IM4.

STAKEHOLDERS AND INTERNATIONAL LINKS

The Danish position is unique in the sense that the universities and industries possess many of the broad-spectrum research competences required for research and development in sustainable food production processes. Consortia need to have a broad involvement of actors with relevant university partners, knowledge institutions, authorities, industry, and commercial companies from the agriculture and food sector and both established and start-ups.

The climate challenge requires internationally concerted actions governed by the UN Climate Action at global scale and by the EU Green Deal from a European perspective. The climate challenge foresees an evidence-based strategy towards climate neutrality based on mitigation of GHG emissions, adaptation to climate change and restoration of damaged services. The transition towards a resilient and sustainable climate smart food and agricultural system is a strategic priority action, as covered in the European Farm to Fork Strategy and the FAO Strategy on Climate Change. In the same way the environmental issues are covered by European directives such as the Water Framework Directive and biodiversity concerns are governed by the EU biodiversity strategy, and these efforts are increasingly embedded in the EU Common Agricultural Policy.

There are various alliances for governing the international cooperation in research and innovation on this issue. At the global scale, the Global Research Alliance (GRA) on agricultural GHG emissions was initiated in 2009 at the COP 15 in Copenhagen and brought more than 3000 experts from 60 countries and partner organisations (i.e., FAO, CGIAR, CCAC) together in a dynamic research community with impact. Denmark is one of the founding fathers and active members of the GRA.

The European partner of GRA is the EU Joint Programming Initiative on Agriculture, Food Security and Climate Change (FACCE-JPI; since 2011), with 24 members including Denmark. In the last 10 years FACCE-JPI initiated joint research in 120 projects by 850 institutions with a 260 million Euro funding, under the umbrella of the Horizon 2020 RTDI framework programme. In the next Horizon Europe programme, climate related RTDI is even more prioritised, in the missions 'Adaptation to climate change' and 'Soil health and food' and in the RTDI topics and partnerships foreseen in the cluster "Food, Bioeconomy, Natural Resources, Agriculture and Environment". The research and innovation activities in Denmark should be seen in the context of these European and global efforts, not least because many of the Danish agro-industrial partners have a large European and global presence, and the innovations and products developed in Denmark will be marketed globally. There is a clear potential for the Danish research and innovation efforts to partner with other leading European and global universities and research institutions for enhancing the needed research capacity. This requires aligning of the Danish research strategy with the European and global research and innovation planning (including FACCE), to enable an international impact by scientific cooperation and by multiplication of the Danish funds with international and private co-funding opportunities.

FINANCIAL PLAN

What should be financed? Land use and agriculture currently account for approx. 35% of GHG emissions in Denmark and is expected to account for more than 40% of emissions in 2030 without mitigation. While some reduction can be reached by political regulation, there is still a considerable need for maturing and implementing innovative technologies in the supply area and understanding the human social aspects motivating behavioural changes in terms of new diets and waste reduction in the demand area. The sector is important for both employment and exports. Currently the sector has a turnover of 368 billion DKK annually, employs 190,000 people and accounts for 170 billion DKK (23%) of Danish commodity exports in 2019.

The required GHG emission reductions can be reached by a combination of many initiatives, for which the impact still needs to be determined more precisely. Simultaneous goals related to biodiversity and environmental impacts further challenge the idea of a single roadmap and points to a reduction strategy consisting of many small steps with research, innovation, and implementation initiatives related to all subsectors and all steps of the value chain.

Many different initiatives should be financed to reach the 2030 and 2050 goals. Financing sources in agriculture and food industry consist of self-financing (loans) and blended finance (public/private financing). Industry investment is moderate, and industry co-financing will be limited for the goals partly because many of them are hard to commercialise (e.g., many biodiversity goals) or distribution is spread on › thousands of SMEs (e.g., genetic improvements). Technology and innovation funding on the low TRLs will rely heavily on public funding. Higher TRLs are supported by strong sector implementation structure, but private co-financing will be limited due to comparatively low profitability margins and investment levels. Private funding for scaling new business models and scaleups, and how clusters can play a vital role in this, should attract special attention.

How can the changes needed to reach the climate goals be financed in food and agriculture? Investing in green development has moved from philanthropy to mainstream, exemplified by the recent private-public partnerships on energy islands and climate investment strategies from pension funds. While this is good news, the investment attractiveness does not relate to all industrial sectors. In a Copenhagen Economics analysis of investment needs and finance sources, agricultural GHG reduction initiatives are expected to be financed by mortgages, business loans, and blended finance in which The Danish Growth Fund and The Danish Green Investment Fund are mentioned as key players. Other sectors rely more on equity, the energy sector showing examples of as much as 50% from equity. This is an indication of the relative attractiveness of sector investments seen from a financial perspective and might be related to the willingness to co-invest in research and innovation.

The financial needs A sustainable food system that continues to play a key role in terms of employees and international competitiveness is estimated to need approx. 12.5 billion DKK annually in required private and public investments to reach the 2030 goals. This figure does not include the goals related to biodiversity. In comparison, it is estimated that the energy sector has an investment need of 180 billion DKK to reach the 2030 goals. These are of course uncertain estimates, but underlines that the realisation of lower GHG emissions along with research of other sustainability targets in agriculture and food products require substantial investments.

Funding research and technology development This roadmap outlines how research and technology development across current subsectors and throughout the entire value chain can contribute to lower GHG emissions, less environmental impact and pollution, and enhanced biodiversity. Further development builds on strong research tradition, as well as strong traditions for implementation. The roadmap outlines research gaps with a private and public funding need for approx. 5 billion DKK annually until 2030, of which a part is already allocated to private and public programs co-funded by universities and industries. However, there is a need for substantial new investments in research capacity at universities, technological institutions, and major industrial players within both research staff and facilities. The need for enhancing research and innovation capacity will also require close collaboration with international research institutions and recruitment of research and technical staff internationally.

Approx. 20% public foundations, 20% private foundations, 30% private research investment and 30% private investment in facilities. For lower levels TRL (up to 4) financing is mainly covered by public and private research foundations. At higher TRL and SRL levels, it will be a combination of private

The annual estimated need for funding and investment in research, innovation and upscaling solutions (2021-2030) to become a world leader in knowledge driven sustainable transformation of the agro-food system. Investment in processing facilities will increase towards 2030 and be lower at the beginning of the period.

	TRL 1-4		TRL 5-9				
	Publ foundations	Priv foundations	Publ foundations	Priv foundations	Priv investments	Processing facility	Total
	m DKK	m DKK	m DKK	m DKK	m DKK	m DKK	m DKK
Land use and management*	150	300	150	600	300	0	1,500
Animal based food production	200	200	400	600	1,200	1,400	4,000
Plant based food production	300	300	300	300	900	900	3,000
Biotech and alternative proteins	400	400	400	-	1,200	1,600	4,000
Total	1,050	1,200	1,250	1,500	3,600	3,900	12,500

* Public "Land purchase" is not included

TRL 1-4 public foundations	Danish National Research Foundation, Independent Research Fund Denmark, ERC, etc.
TRL 1-4 private foundations	Novo Nordisk Foundation, Villum Foundation, Carlsberg Foundation, B&M Gates Foundation, etc.
TRL 5-9 public foundations	Innovation Fund Denmark, GUDP, MUDP, Horizon Europe, etc.
TRL 5-9 private foundations	Landbrugets fonde, smaller foundations, etc.
TRL 5-9 private investments	Company research, vækstfonden, Danmarks Grønne Investeringsfond and private technology investments, incl. agriculture

co-funding and support from Innovation Fund Denmark (IFD), demonstration programs (GUDP and MUDP), EU Horizon Europe, The Danish Growth Fund, The Danish Green Investment Fund, Carlsberg, Villum Foundation, Novo Nordisk Foundation, as well as export acceleration programs supporting further development.

Funding for demonstration and implementation

When it comes to adaptation and product customization of proven Danish technologies to new markets, there is a financing gap since this activity falls between innovation (IFD, etc.) and export (EKF etc.) support actions. Many early adaptors in export markets take a considerable risk on a solution that might work in Denmark but needs to be adapted to the specific local context with different regulatory and technology requirements. A dedicated support program for the initial international demonstration of a specific green technology will make a significant impact on exports.

Denmark is acknowledged for having a unique and effective agriculture knowledge and an innovative eco-system. Production levy funds play a significant role in financing research, innovation, demonstration, and knowledge transfer. In this way, all primary producers in the different sectors contribute financially and this also enhances "ownership and awareness" of research and innovation. Promilleafgiftsfonden for Landbrug and the production levy funds will raise investments in climate projects in the coming years.

Funding for commercialisation and entrepreneurship

New research-based knowledge, as well as both national and international demand for innovative end-user products, processing equipment and business models, lay the basis for industry and university spinouts and an increase in number of start-ups. The innovation level and thus potential international competitiveness of these companies will be strengthened by the underpinning research and the competences of the university sector. Accelerating these companies with a focus on scalability will require both public soft funding, and equity investors. While good initiatives already exist, it is key to develop targeted measures that contribute to the future development of an innovative sector with high-value propositions. Compared to other Scandinavian and other European countries that Denmark typically compares itself with, Danish agri-food start-ups and scale-ups have difficulty in attracting needed competences and capital to scale their business with negative effects on global impact, job creations etc. Meanwhile, research and experience show that innovation clusters like Food & Biocluster Denmark play a vital role in developing a well-functioning, innovative and competitive ecosystem with multiple stakeholders; academia, public, small and medium-sized enterprises (SME) and corporates from Denmark and abroad. The core competences of clusters are the same that are needed to match diverse types of Danish and foreign investors and private funding with start-ups and scale-ups. Moreover, lighthouses specialised in areas like plant-based products are needed to attract foreign investors, entrepreneurial talent, innovative solutions, and foreign corporates to Denmark within megatrends.

New financial instruments and sector specific instruments When the market pulls and the willingness to pay for mitigating GHG emissions and environmental impacts is present, new financial instruments may be a solution. The Danish Nature Fund, where private individuals 'buy' forest, which is in principle a donation, is an example with a broad range of investors. Organisation into cooperatives is another possibility with a long tradition in the Danish agriculture and food industry. Close partnerships such as products from Gram Slot/Rema 1000 is yet another. New financial models are coming up as marketing carbon credits allocated to individual farmer actions, although this will require verified certification schemes and alignment with other incentives. These models need to be aligned with international standards, and such efforts may support the out-scaling of Danish research and innovation for the global market for agricultural solutions thus further supporting Danish jobs and exports.

CONCLUSION

An Innomission describing a green transition of the agriculture, food and land use sector is a major and highly complex task. Therefore, it is not meaningful to make simple conclusions nor to establish a sequential roadmap. Instead, the focus has been on creating a roadmap with four complementary tracks and an additional cross cutting section, incompassing the complexity and focusing on shaping the future instead of the impossible task of predicting it.

The process of making this roadmap was led by Aarhus University, Technical University of Denmark, University of Copenhagen and SEGES, but it has been a collaborative effort with contributions from more than 200 researchers from eight Danish universities, sector organisations and industries. All have given highly valuable input that enabled the writing of this roadmap. This has included several workshops, more than 150 topics at the offset and 450 pages of track descriptions. Industry, researchers, and organisations have been informed, involved, and consulted throughout the process to make sure that the roadmap truly represents the interests of all stakeholders.

Summary of impact for each track

A: LAND USE AND MANAGEMENT About 60% of Danish land is used for agricultural production. This makes Denmark belong to the most intensively cultivated countries in the world. Therefore, the way we use and manage this land and the remaining 40% taken up by cities, infrastructure, forestry, and nature is important for a sustainable development of nature and society and for achieving carbon neutrality, low environmental impact and good ecological status of terrestrial and aquatic ecosystems while maintaining a high production and securing jobs and economic growth. The numerous measures needed involve land distribution reforms, rewetting of organic soils, changed drainage practices, afforestation and obtaining measured impacts of different land use management strategies. It also involves developing new cropping and fertilisation systems with greater focus on biodiverse arable systems and perennial crops with greater productivity and resource use supporting intiatives in other tracks.

B: ANIMAL-BASED FOOD PRODUCTION The demand for animal-based products is increasing, and Denmark is in a unique situation to become an international frontrunner on the green transition of animal food production. The livestock sector has traditionally been playing a key-role in the supply chain from farm to fork due to increased global demand for dairy, meat and eggs, and the green transition of the sector is part of the solution towards a green transition of Danish agriculture and land use. Animal food production is a significant contributor to GHG emissions and nutrient, ammonia, and pesticide pollution. However, the sector is simultaneously a key player supporting biodiversity through grazing of nature areas. Thus, with the proper technological and biological innovations of the Danish livestock sector, Denmark will be able to pave the way for a sustainable livestock production with low CO_2 output per kg product and with regards to animal health and welfare, creating jobs and continue to be a significant contributor to Danish exports, employment and economy with an end-goal of providing tasty, healthy and nutritious animal-based foods.

C: PLANT-BASED FOOD PRODUCTION Plant-based food production is an important part of the solution towards a continued green transition of Danish agriculture and land use. Consumers are increasingly demanding more plant-based food products, Danish farmers are very interested in growing more food crops to meet this demand, the soil and climatic conditions for plant production are optimal in Denmark, and many start-ups and established food companies are already developing a wide range of plant-based food products. Substantial investments in research, innovation and implementation will make it possible to exploit the full growth potential of the plant-based food value chain and bring Denmark in a position to achieve a global market share of plant-based food between 1% and 3% coupled with the creation of between 9,000 and 27,000 new jobs.

D: BIOTECHNOLOGY-BASED FOOD PRODUCTION AND ALTERNATIVE PROTEIN SOURCES Technological development across the food sector opens for sustainable ways to produce safe, tasty and healthy food. These technologies have the potential, along with development in production of plant and animal-based food, to ease the transition towards a more sustainable food production in Denmark and internationally. Novel microorganism- and animal cell-based alternatives to animal-based food are projected to reach 10-20% of global protein consumption by 2035. Functional food ingredients, cultures and additives are part of this value pool. However, this demands massive investments in research and innovation within biorefining, cellular agriculture, animal-cell based production, microbial and enzymatic upgrading of current and alternative feedstocks and of inclusion of alternative ingredients from e.g., insects and blue biomasses. While research and innovation within traditional plant and animal production have a long history, novel and alternative ways to produce food are still in their early phase and typically at low technology readiness levels. However, Denmark has a large and so far, unutilised potential to become a frontrunner in this development.

CROSSCUTTING ASPECTS Reaching the 2030 and 2050 ambitions when it comes to goals for climate, biodiversity, and environment, while maintaining high productivity, jobs and economic growth constitute a great and highly complex challenge. It demands a holistic view and involves consumer acceptance and involvement of industry, interest organisations and people from academia with diverse backgrounds. There is a need for disruptive thinking and collaboration between expertise that may not traditionally have worked together thus involving engagement of people from e.g., humanity and social sciences. Denmark has a strong tradition for developing innovative technologies and high-level research within agricultural sciences. However, we propose that Denmark should have the ambition to become a world leader in implementation also, i.e., getting from technical innovation to sustainable transformation of the agri-food system. For that to happen data driven governance is a prerequisite and success depends on cross-disciplinary collaboration involving work proposed in all tracks in this roadmap.