WHITE PAPER

AgriFoodTure

ROADMAP FOR SUSTAINABLE TRANSFORMATION OF THE DANISH AGRI-FOOD SYSTEM

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This white paper is an extended version of the submitted Roadmap for the Innovation Fund Denmark Innomission III on climate- and environment-friendly agriculture and food production. In particular many of the solutions presented in the Roadmap are here further detailed.

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

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EXECUTIVE SUMMARY

The green transition of the agriculture, food and land use sector is a major and highly complex task. Meeting the combined challenges of climate change, biodiversity loss, and land-system change requires for actors and agencies in the agri-food complex to rethink, redeploy, and reinvent instruments and mechanisms of governance at all scales, local to global to orchestrate far-reaching green transitions (or transformations) of its socio-technical and socio-ecological systems.

Denmark has a unique potential to become an important leader within the green transition of agriculture, land use and food clusters. This demands development and implementation through disruptive innovative solutions. To bridge knowledge gaps, we have identified four major tracks and additional crosscutting aspects, which together contribute with solutions that will enable reaching the national and global 2030 and 2050 missions and goals:

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

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.

The proposed research and innovations within land use, land management and agricultural production systems contribute significantly both to national and international missions. However, investments in research and innovation are essential to achieve the goals in order to provide the basis for substantial reductions in GHG emissions, nitrogen and phosphor loadings to the freshwater and marine ecosystems, and pesticide use, as well as changes in land use and management supporting biodiversity.

LAND USE AND MANAGEMENT
About 60% of the Danish land is used for agricultural production. This makes Denmark one of 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 fertilization systems with greater focus on biodiverse arable systems and perennial crops with greater productivity and resource use supporting initiatives in other tracks.

ANIMAL-BASED FOOD PRODUCTION
The demand for animal-based products is increasing, and Denmark is in a unique position to become an inter-national 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 products, 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 biodi-versity e.g., 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. This allows for production with low CO2 output per kg product, focus on animal health and welfare, and will create 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.

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.

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 microorganisms and animal cell-based alternatives to animal-based food are projected to reach 10-20% of the global protein consumption by 2035. Functional food ingredients, cultures and additives are part of this value pool. However, for this to happen it 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, unutilized potential to become a frontrunner in this development.

CROSSCUTTING ASPECTS
In addition to the four tracks, crosscutting aspects on governing the agri-food transition, life cycle assessment, digitalization, economic instruments, and resource efficient food processing are described. Reaching the 2030 and 2050 ambitions when it comes to goals for climate, biodiversity, and environment, while maintaining high productivity, jobs and economic growth constitutes 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 too, 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.

INTRODUCTION

Scientific 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 9.8 billion by 2050 (United Nations, 2017). 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 (Fukase & Martin, 2017). This is projected to require an increase in overall food supply in Denmark of 45% by 2050 (Searchinger et al., 2019, 2021). 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 (Clark et al., 2020). 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 (Crippa et al., 2021). The imperative 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 (Rockström et al., 2009; Smith & Gregory, 2013; Clark et al., 2020). 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 institutes (Danish Association of Research and Technology Organizations), local and national authorities, and non-governmental organizations. The task is too big and too complex to solve in individual groups with specialized 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 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 roadmap 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 (SDGs 2, 4, 7, 8, 9, 12, 13, 15, 17).

This roadmap is based on collaborative efforts with contributions from close to 300 researchers from Danish universities with input from industry and NGOs (see contributor list at end of document). 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 maximized 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 leader 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 relatively 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 (Food Nation, 2017; Searchinger et al., 2021). 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 and beyond the sector. Examples include major reductions in use of pesticides and antibiotics in Danish agriculture compared to similar countries, 50% reduction in nitrogen loads to the aquatic environment over 30 years, and a doubling of organically farmed land within the last 12 years (Nielsen et al., 2020; Landbrugsstyrelsen, 2021).

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 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.

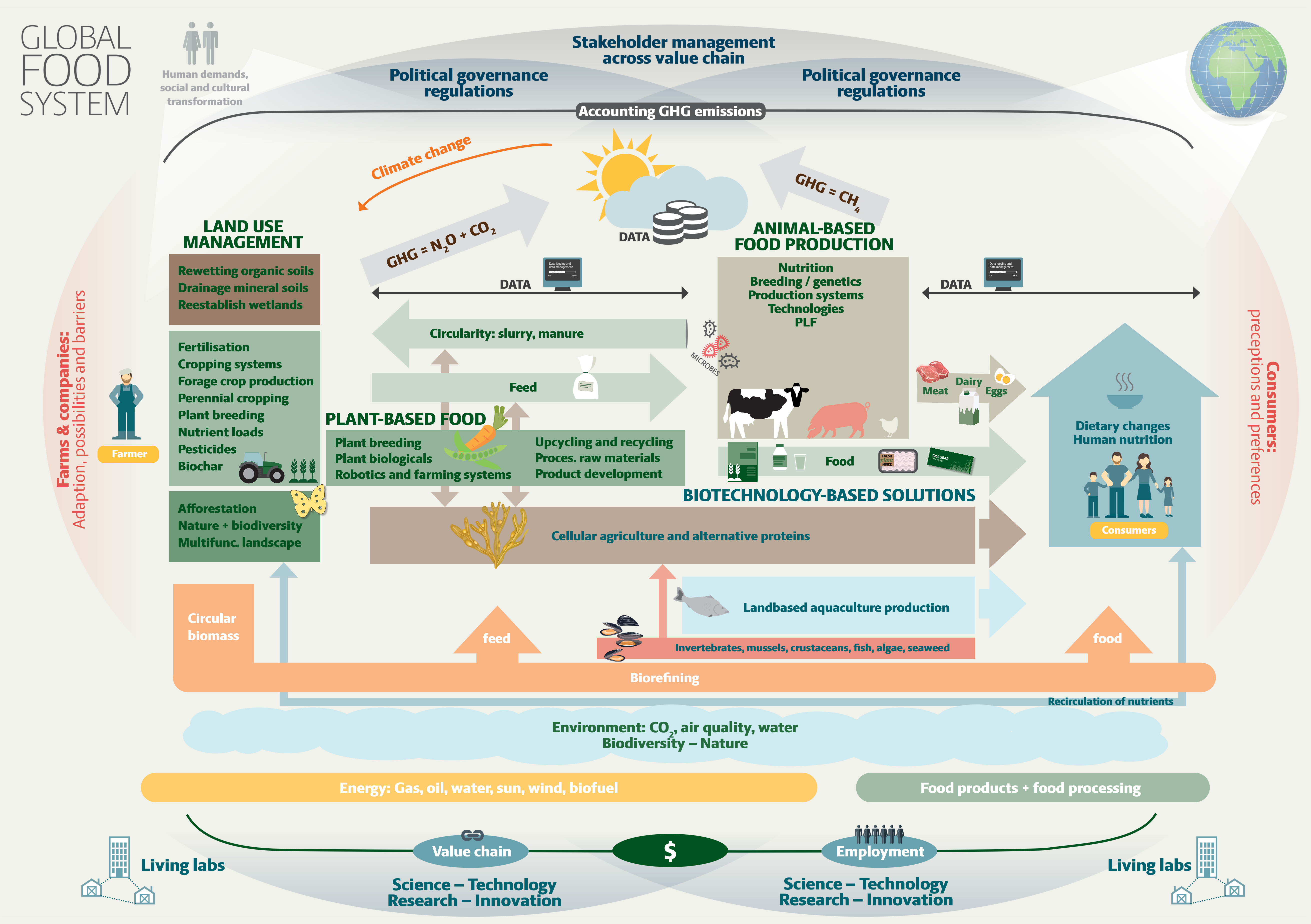


FIGURE 1
Global food system map illustrating the complex interplay between animal and plant-based food production, land use and management, and biotechnological innovations. Solutions can only be obtained in collaboration between sectors and require considerable consumer involvement.

MEASUREMENT OF SPECIFIC IMPACT OF ROADMAP 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. Simultaneously with reducing global GHG emissions we should also 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, crosscutting 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). 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 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:

- 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.
- Meeting the requirements of the EU Water Framework directive of good ecological status of the aquatic ecosystems and of groundwater for human use.
- reach 24% reductions of ammonia emissions by 2030 as compared with 2005 levels,
- reach the ambition to become world leading within circular economy by 2030, and
- contribute with our share in turning 30% of Europe's land into protected areas, reduce pesticide use by 50%, reverse the decline of pollinators 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 (Nielsen et al., 2020). 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 (Nielsen et al., 2020). The proposed innovations 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 (Nielsen et al., 2020). 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, feed 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 and sustainable operators recycling excess nutrients to agricultural land and with a low GHG emission. 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 (Odgaard et al., 2019). 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.

Estimated contributions to sustainability targets nationally

The proposed research and innovations of changes in land use, land management and agricultural production systems provide the basis for substantial reductions in GHG emissions (Table 1), nitrogen loadings to the marine ecosystems (Table 2) and pesticide use (Table 3) as well as changes in land use and management supporting biodiversity (Table 4). These estimates are all based on territorial effects in Denmark associated with Danish agriculture and land use for both feed and food production. The effects are based on the estimated potentials of technologies and management changes on the impact categories as well as estimates of how quickly these can be implemented in a situation with

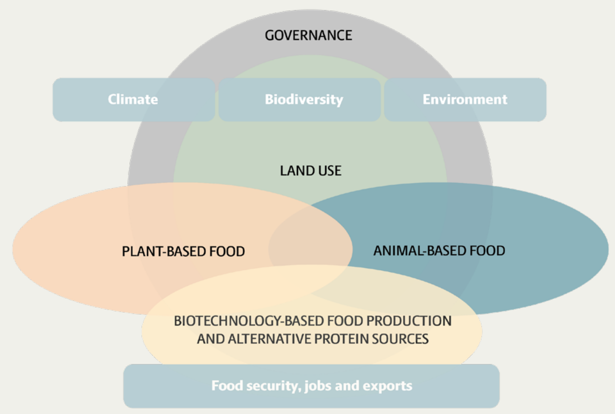


FIGURE 2
A green transition of the agriculture and food sectors will depend on strong collaboration between researchers and commercial operators across the different tracks. Utilising the potential for synergy will provide tools and solutions to reach the goals for climate, biodiversity, and environment,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

sufficient investments in technological development and incentives to drive the implementation.

The reductions in GHG emissions in both 2030 and 2050 result primarily from five main categories: enteric fermentation, manure management, fertilization, organic soils and sequestration of carbon in soils (Table 1). The estimates are based on an assumed livestock production equivalent to the current production, but a reduced land area used for production of livestock feed, giving room for increased area for plant-based food production (300,000 ha in 2030 and 600,000 ha in 2050) and for land use changes to support biodiversity through rewetting organic soils, set-a-side and afforestation (Table 2). The estimates do not make specific assumptions on the proportion of land farmed organically, but consider that this proportion will likely increase over time.

The reductions in enteric fermentation are assumed to be at least 40% by 2030, which is based on an assumed 50% reduction in emissions from dairy cattle from conventional farming, but only 20% reduction in emissions from dairy cattle from organic farming, resulting from a combination of changes in feeding practices, livestock breeding and use of feed additives. For grazing ruminant livestock, including cattle and sheep, reductions will be considerably lower. By 2050, this reduction is assumed to increase to at least 70% based on similar, but improved, technologies.
The manure management technologies primarily target reductions in methane emissions, since nitrous oxide emissions from the largely slurry-based manure management systems in Denmark are thought to be lower than currently estimat-

ed in inventories, and this is currently being investigated. The technologies used will encompass a range of different technologies, such as cooling, biogas, acidification, cover on slurries combined with technologies for methane oxidation, but essential to all of these technology packages is quick removal of manure from the livestock housing combined with cleaning of surfaces in the house. This may eventually reduce emissions by more than 90% in 2050 and be applicable in both conventional and organic farming; however, it will require time to phase in the technologies in all farming systems.

A considerable reduction in nitrous oxide emissions (30-40%) can be achieved with use of nitrification inhibitors, which are already available, but require documentation for their effective and safe use. Additional reductions will come from improved manures, novel fertilisers, better timing of fertilisation and better soil structure with less risk of nitrous oxide emissions, combined with enhanced use of perennial cropping and other crops with lower risk of nitrous oxide emissions. By applying new and improved traditional breeding technologies, optimizing management practices, improving farming systems, reducing waste, upcycling side streams and applying plant biologicals, artificial intelligence (AI) and robotics, it is expected that the overall efficiency of the increased high-value food crop production for human consumption will increase by 10% in 2030 and 20% in 2050. This will primarily contribute to reducing nitrous oxide emissions with an overall reduction of 0.18 Mt CO_2-eq for an additional 300,000 ha of food crops in 2030 and 0.45 Mt CO_2-eq for an additional 600,000 ha of food crops in 2050. Together with other measures this is estimated to reduce nitrous oxide emissions by 40% in 2030 and 70% in 2050. These emission reductions reflect larger reductions in conventional than in organic farming, due to differences in availability of technologies.

It is estimated that rewetting of all agricultural organic soils will reduce emissions from these lands by 80%, since the rewetting will increase methane emissions offsetting some of the benefits of lower CO_2 and nitrous oxide emissions from the rewetting. With a considerable effort of speeding up processes on rewetting organic soil with the largest emissions, it is estimated that a 30% reduction is achievable by 2030.

There are also minor reductions in emissions from other sources of nitrous oxide emissions related to crop residues and losses of nitrogen in ammonia volatilization and nitrate leaching (Table 1). The reductions in emissions from crop residues are implemented primarily through increased use of crop residues for biorefining and biogas, whereby this source for soil nitrous oxide emissions is reduced. The reductions in indirect emissions of nitrous oxide from ammonia volatil-

TABLE 1 Estimated potentials for reducing net agricultural GHG emissions in Denmark relative to emissions in 2018.

	Baseline Mt CO_2-eq	Reduction %		Reduction Mt CO_2-eq	
Source	2018	2030	2050	2030	2050
Enteric fermentation (CH_4)	3.77	40	70	1.51	2.64
Manure management (CH_4, N_2O)	2.81	50	90	1.41	2.53
Fertilization (N_2O)	2.83	40	70	0.91	1.60
Crop residues (N_2O)	0.61	10	40	0.06	0.24
Ammonia volatilization (N_2O)	0.34	20	40	0.07	0.13
Nitrate leaching (N_2O)	0.33	10	30	0.03	0.10
Liming (CO_2)	0.24	10	20	0.02	0.05
Energy use (CO_2)	1.25	50	100	0.62	1.25
Organic soils (CO_2, N_2O)	5.75	30	80	1.73	4.60
Soil carbon (CO_2)	-	-	-	1.80	4.30
Total	**17.37**	**48**	**100**	**8.16**	**17.44**

ization and nitrate leaching result from measures to reduce these losses, primarily through changes in manure handling for the ammonia volatilization and changes in cropping systems and fertilization for the nitrate leaching (Table 2).

The use of fossil fuels for energy supply is assumed to be gradually phased out with 50% by 2030 and completely by 2050, initially through use of biofuels and over time increasingly by electrification of farm machinery and use of technofuels based on renewable energy.

Soil carbon is estimated to be enhanced by 1.80 and 4.30 m tons CO_2 annually by 2030 and 2050, respectively. This will originate partly from enhanced soil carbon from perennial cropping systems and setting aside agricultural land for nature and afforestation. Using the standard values for enhanced soil carbon from Eriksen et al. (2020) the estimated increases in these areas from Table 4 will contribute 0.66 and 1.31 m tons CO_2 annually in 2030 and 2050, respectively. The enhanced used of perennial cropping systems will also enhance soil carbon, and here a conservative estimate of increased soil C of 0.6 ton C/ha annually is used (Taghizadeh-Toosi et al., 2016). With the estimated increases in perennial cropping presented in Table 4, this will increase soil carbon corresponding to offsetting 0.66

TABLE 2 Estimated reductions in nitrogen loadings (tons N per year) to the marine ecosystems in Denmark compared to baseline loading by 2027 of 52,000 tons N per year.

Category	Source	2030	2050
Land management	Improved arable cropping systems	2,200	2,500
	Perennial cropping systems	1,000	2,000
	Improved fertilizers/ manures	500	1,000
	Precision fertilization technologies	500	1,000
Increased retention	Re-established wetlands	1,500	3,000
	Constructed wetlands/ filters	1,500	3,000
Land use change	Set-a-side	750	1,500
	Afforestation	750	1,500
Total		**8,750**	**15,500**

and 1.10 m tons CO_2 annually. The rest of the increase in soil carbon will primarily come from use of biochar, which is then estimated at 0.49 and 1.89 m tons CO_2 annually in 2030 and 2050, respectively. Assuming a conversion rate of carbon in biomass to biochar through pyrolysis of 40%, the current amount of manure after biogas digestion would have a potential of 0.69 m tons CO_2 annually. The current use of straw and wood chips for heating purposes (incineration) would have a potential for offsetting 0.97 and 1.45 m tons CO_2 annually, respectively. This gives a total potential for biochar of 3.11 m tons CO_2 annually from current waste biomasses, without compromising other sustainability challenges and with recycling of nutrients, and this exceeds the required amounts for biochar for achieving carbon neutrality giving some room for manoeuvre.

Achieving the objectives of the Water Framework Directive requires substantial reductions in nitrogen loadings to the marine environments in the order of up to 15,000 tons N annually on a national basis; however, with substantial variation between catchments. Therefore, measures to achieve the targets may have to vary considerably between catchments depending on required reductions and the possibilities for affecting loadings through changes in land management, land use and changes in drainage infrastructures and wetlands that increase the denitrification of leached nitrate before it reaches the marine environment (increased retention). A mixture of different measures will likely be needed to meet the objectives (Hashemi et al., 2018).

Table 2 illustrates how the reductions in N loadings to the marine environment may be achieved through different measures that integrate both existing and new measures within agricultural land use and management. Estimates for existing measures are based on Eriksen et al. (2020), whereas novel measures are based on conservative estimates. Improved arable cropping systems for both feed and food production will be able to reduce nitrate leaching by improving crop N uptake in autumn through earlier sowing of winter cereals and improved cover crops with greater and more stable nitrate leaching reductions. Perennial cropping systems by nature have lower nitrate leaching than the typical arable cropping systems used in Denmark (Manevski et al., 2018), and the projected increase in these systems will therefore reduce nitrate leaching. There are also possibilities for improving utilization of manures resulting in lower nitrate leaching, e.g., through use of nitrification inhibitors, and better targeting of fertilizers in time and space may also reduce nitrate leaching losses. Land use change in terms of set-a-side and afforestation will also reduce nitrate leaching, and the estimates in Table 2 are based on the estimated land use changes in Table 4. Increased retention can be achieved by re-establishing wetlands in river valleys, where nitrate is retained and denitrified, or by establishing constructed wetlands or filter systems on farmland collecting and treating water from subsurface drainage systems (Hoffmann et al., 2020).

Pesticides are used for controlling weeds, pests and diseases. There is political ambition to phase out use of chemical pesticides, they are prohibited in organic farming and it is expected that consumers will demand that plant-based food products should be produced without the use of pesticides. Some herbicides are used for other purposes than controlling weeds. This is particularly the case in conservation agriculture, where herbicides (typically glyphosate) are used to terminate cover crops, since ploughing cannot be used in this system. Therefore, phasing out chemical pesticides will need to involve a range of changes in cropping systems for both feed and food production as well as technologies to substitute their use (Table 3).

Perennial cropping systems based on grass crops have considerably lower requirements for pesticides than annual arable cropping systems, and the increased use of these systems will therefore reduce chemical pesticide use. Increased plant species and diversity of arable cropping system for both feed and food production will increase competitiveness to weeds and reduce pressures of pests and diseases, lowering the need for chemical pesticide use. Plant biologicals may be suitable substitutes for chemical pesticides to control pests and diseases, which may also be partly controlled by improved plant resistance breeding.

TABLE 3 Estimated contributions of various measures and technologies to reduce pesticide use (percent of current use).

Measure	2030	2050
Perennial cropping systems	10	15
Diversity of arable cropping	5	20
Plant biologicals	5	10
Plant resistance breeding	10	15
Precision technologies	15	30
Total	**45**	**90**

In addition, precision technologies through sensor systems combined with AI, robotics and mechanical tools will be particularly suitable for substituting herbicide use in both feed and food production.

Increased biodiversity can be achieved through both land sparing and land sharing (Table 4). Land sparing is the situation, where increased productivity on the existing agricultural land allows current agricultural land to be taken out of agricultural production, which in this case is for re-wetting organic soils and some of the mineral soils (in total 250,000 ha) as well as setting aside land for afforestation and dryland nature areas (estimated at in total 200,000 ha). Land sharing involves increasing biodiversity on existing land, which is often seen as requiring reduction in agricultural productivity. However, there are options of increasing the plant diversity of agricultural cropping systems for both feed and food production that will allow increases in both productivity and allow increased room for biodiversity. This is considered to be achieved through measures such as agroforestry and increased biodiversity of both perennial and annual cropping systems (in total 1,200,000 ha in 2030 and 2,400,000 ha in 2050).

Estimated contributions to sustainability targets globally

Besides the contributions to national sustainability targets there is a large potential for the Danish agriculture and food sector to contribute to reducing global GHG emissions and achieving global sustainability targets that should also be taken into account.

More than 70% of the soy that is imported to Denmark comes from Argentina and Brazil (Callesen et al., 2020). If we in Denmark by 2030 allocate 294.000 ha for producing grass which is processed into protein concentrate, we

TABLE 4 Changes in land use and management (1,000 ha) of currently used agricultural land contributing to improved biodiversity in the agricultural landscape. The current agricultural land area in Denmark is 2.62 m ha.

Category	Source	2030	2050
Land sparing	Rewetted areas	100	250
	Set-a-side	50	100
	Afforestation	50	100
Land sharing	Agroforestry	50	100
	Biodiverse perennial cropping	300	500
	Biodiverse arable feed cropping	500	1000
	Biodiverse arable food cropping	150	350
Total		**1,200**	**2,400**

will be able to replace 40% of the imported soy used as feed for pigs, cattle, poultry and fish, reduce the global area required for producing soy by 162.000 ha and reduce net global greenhouse gas emissions by 1,8 Mt CO_2-eq (estimate based on Scenario 2 in Jørgensen et al, 2020 coupled with high carbon footprint of grass protein in Dalsgaard et al, 2020 and LCA results for soybean meal in Mogensen et al, 2018).

Correspondingly, the allocation of 454.000 ha to produce grass by 2050 will be able to replace 90% of the imported soy, reduce the global area for producing soy by 365.000 ha and reduce net global GHG emissions by 5,7 Mt CO_2-eq (estimate based on Scenario 4 in Jørgensen et al, 2020 coupled with low carbon footprint of grass protein in Dalsgaard et al, 2020 and LCA results for soybean meal in Mogensen et al (2018).

There is a large potential for reducing global greenhouse gas emissions with more plant-based food production (Henriksen, 2021). If we in Denmark by 2030 allocate between 100.000 and 150.000 ha (average 125.000 ha) for growing protein-rich crops that are used for the manufacturing of gently processed, nutritious and tasty plant-based food products of high quality for both domestic use and export to substitute meat consumption, this would reduce the global area required for producing feed by between 0,8 and 4,7 million ha (average 2.2 million ha) and reduce global greenhouse gas emissions by between 4,7 and 11,5 Mt CO_2-eq (average 7,8 Mt CO_2 eq). Besides contributing to reducing the climate impact of the global food system, the reduced area required for feed would also contribute

TABLE 5 Estimated global land use and GHG emission reductions.

Scenario year	GHG emission reduction measures	Allocated domestic area (ha)	Reduced global area required for producing feed (ha)	Total agricultural value chain GHG emissions from production in Denmark (Mt CO_2-eq)	Net reduced global GHG emissions from prodcution in Denmark (Mt CO_2-eq)
2030	Grass production in Denmark substituting imported soy used for feed (*)	294,000	162,000	0.7	1.8
	Plant-based food production in Denmark substituting global meat consumption (**)	125,000	2,200,000	0.9	7.8
	Increasing the efficiency of food crop production (***)		250,000	0	0.7
	Biotechnology-based food production in Denmark substituting global meat consumption (****)	50.000	470,000	2.2	1.8
	Total(*****)	469,000	3,082,000	3.8	12.1
2050	Grass production in Denmark substituting imported soy used for feed (*)	454,000	365,000	0.1	5.7
	Plant-based food production in Denmark substituting global meat consumption (**)	200,000	3,550,000	1.6	12.4
	Increasing the efficiency of food crop production (***)		750,000	0	2.5
	Biotechnology-based food production in Denmark substituting global meat consumption (****)	100,000	1,000,000	1.5	7.2
	Total(*****)	754,000	5,655,000	3.2	27.8

(*) Grass produced in Denmark is replacing 40% and 90% of the imported soy used to feed pigs and chickens in 2030 and 2050, respectively
(**) Protein-rich crops grown in Denmark is used for manufacturing of plant-based food products for both domestic use and export and replacing the consumption of meat (40% beef, 40% pork and 20% chicken)
(***) By applying new and improved traditional breeding technologies, optimizing management practices, improving farming systems, reducing waste, upcycling side streams and applying plant biologicals, AI and robotics, it is assumed that the efficiency of food crop production will increase by 10% in 2030 and 20% in 2050
(****) Estimate of potential for biotechnology-based food production in Denmark to replace the consumption of meat (40% beef, 40% pork and 20% chicken) based on LCA study of cultivated meat assuming 50% transition to renewable energy by 2030 and full transition to renewable energy by 2050
(*****) Since the estimates for grass production, plant-based food production and biotechnology-based food production are based on individual LCA studies with different assumptions, boundary conditions and emission factors, they are not directly comparable with each other.

significantly to improve water resources and biodiversity. By applying new and improved traditional breeding technologies, optimizing management practices, improving farming systems, reducing waste, upcycling side streams and applying plant biologicals, AI and robotics, it is assumed that the efficiency of food crop production will increase by 10% in 2030. This will result in a further reduction of global area required for producing feed between 75.000 and 425.000 ha (average 250.000 ha) and reduction of global greenhouse gas emissions by between 0,5 and 1,1 Mt CO_2-eq (average 0,7 Mt CO_2-eq).

By 2050 it is projected that the area allocated for protein-rich food crops has increased to approximately 200.000 ha. This would result in a total reduction of the global area required for producing feed between 1,5 and 5.6 million ha (average 3.6 million ha) and a reduction of global greenhouse gas emissions by between 9,4 and 15,3 Mt CO_2-eq (average 12,4 Mt CO_2-eq). With a total increase in the efficiency of food crop production by 20% in 2030 it will be possible to further reduce the global area required for producing feed by between 0,3 and 1,2 million ha (average 750.000 ha) and reduction of global greenhouse gas emissions by between 1.9 and 3,0 Mt CO_2-eq (average 2,5 Mt CO_2-eq).

As an example of how biotechnology-based food production in Denmark could contribute to global sustainability targets, the results from a recent LCA study on cultivated meat have been applied to estimate the potential of cultivated meat produced in Denmark to reduce global land use and greenhouse gas emissions (Sinke and Odegard, 2021). By assuming a 50% transition from a global stated policies electricity mix coupled with heat from natural gas to solar and wind electricity coupled with geothermal heat, and allocating 50.000 ha to feedstock for domestic production of cultivated meat in 2030, the global area required for producing feed could be reduced by 470.000 ha and global greenhouse gas emissions could be reduced by 1.8 Mt CO_2-eq.

Correspondingly, assuming a full transition to solar and wind electricity coupled with geothermal heat, and allocating 100.000 ha to feedstock for domestic production of cultivated meat in 2050, the global area required for producing feed could be reduced by 1.000.000 ha and global greenhouse gas emissions could be reduced by 7.2 Mt CO_2-eq.
Taken together the replacement of imported soy with domestic grass coupled with plant-based and biotechnology-based food production will be able to reduce the global area required for producing feed by 3,1 million hectares in 2030 and 4,7 million hectares in 2050, and reduce net global GHG emissions by 10,6 MtCO_2-eq in 2030 and 27,8 MtCO_2-eq in 2050, corresponding to 70% and 160% of current emissions from Danish agriculture, respectively.

Since the global emission reduction potential is much larger than the national emission reduction potential, it should be considered how global emission reductions could be accounted for and incentivized to support the implementation of the most efficient measures for reducing global GHG emissions and optimizing environmental benefits.

TRACKS

In the following sections each of the four tracks and a common crosscutting section are described with their own 2030 goals and 2050 vision, 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**

The land area in Denmark is a highly cultivated landscape, with 59.8% agriculture, 13.8% urban areas and infrastructure, 13.1% forests and 9.0% nature areas (Danmarks Statistik, 2020). About 11.3% of the agricultural area is used for organic farming, with a high proportion used for dairy farming or extensive grazing (Landbrugsstyrelsen, 2020). Of the 2.6 m ha in agricultural production, 0.17 m ha are drained organic soils with estimated annual GHG emissions of 5.7 Mt CO_2-eq (Gyldenkærne, 2019). The agricultural land is the source of N_2O emissions corresponding to 4.3 Mt CO_2-eq annually (Nielsen et al., 2020). The land is source of nitrogen (N) and phosphorus (P) loads to the aquatic environments, and a major challenge under the Water Framework Directive is to reduce these loads with a targeted reduction of 15,300 tons N to the marine environment, corresponding to 33% average reduction in N loads from the agricultural land, but with large differences between individual catchments (Odgaard et al., 2019). There are also considerable contributions of phosphorous from agricultural land to the aquatic ecosystems that negatively affect ecosystem functions (Andersen and Heckrath, 2020). The pesticide use in Danish agriculture has been steadily decreasing with sale of active compounds during 2015-2019 on average 2.4 m kg/yr. (Miljøstyrelsen, 2021) and a targeted reduction of 50% by 2030. The EU biodiversity targets stipulate that at least 30% of the land should be protected, and one third of the protected areas should be strictly protected. The national goal is of 1.3 m ha protected and 430,000 ha strictly protected nature.

Sustainability and reduction targets can only be achieved through changes in landscape structure, functions, management, and associated governance. This involves efforts related to land use (restoring larger and smaller natural wetlands in the landscape, rewetting organic soils, construction of different types of constructed wetlands (e.g. surface constructed wetlands, bioreactors, saturated and integrated buffer zones), drainage of mineral soils, agricultural land management (arable, forage and perennial crops, fertilization, plant breeding, nutrient cycling) and landscape and biodiversity management (governance, afforestation, land sparing and management for biodiversity).

The objective of this track is to develop technological and governance solutions that will allow for 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 workstreams

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

TABLE 6 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.

Objectives and goals

Denmark is committed to reducing GHG emissions by 70% before 2030 and to reach net-zero emissions by 2050. In addition to overall reductions of GHG emissions and discharge, there is also commitment to increase circularity, to reduce nutrient pollution, to stop the decline in biodiversity and to secure more high-value nature. The goals of the green research strategy "Green Solutions of the Future" and of the innovation support in the "Innomission-roadmaps" – including mission 3 "Climate- and environment-friendly agriculture and food production" – is to support green research and innovation partnerships that contribute to reaching these goals while both 1) strengthening environment and nature and 2) contributing to increased competitiveness of Danish business and industry. Within this green framework, the overall goal is to search for innovative solutions within "Land use and management". Many of the solutions related to climate change mitigation and adaptation, environment and nature are specifically related to land use.

Because agricultural land use is the major source of nitrous oxide (N_2O) emissions and the major source or sink of CO_2 related to stock changes in soil and vegetation (Campbell et al., 2017), the management of the land area is key to meeting the strategic goals of the mission. In order to reduce GHG emissions, protect biodiversity, and minimize N and P loads to freshwaters and the sea, while still upholding an efficient, productive and economic sustainable agricultural production, it is necessary to achieve a more optimal use and management of the land area, where the functions of the land is optimized from a holistic sustainability perspective supported by innovative technologies (Zak et al., 2018; Carstensen et al., 2020, 2021). As solutions need to be implemented in land areas with numerous conflicting interests, solutions will inevitably imply the question of land sharing, i.e., functional integration, or land sparing, i.e., functional segregation. From the perspective of reducing climate and nutrient impacts, agricultural production should be concentrated on land with the most favorable natural and agricultural conditions for retention, carbon rich wetland areas need to be taken out of production, former wetland areas must be rewetted as they can deliver multifunctional solutions on climate, nutrient retention and biodiversity, and larger continuous areas for biodiversity conservation must be established, etc. (Hoffmann et al., 2020).

Increased production will mean that the same amount of biomass can be produced on a smaller area and allow for setting aside more area for nature. This must be done while maintaining the functional diversity of the cropping systems to make them resilient to climate change and avoiding to a great extent environmental emissions, nutrient losses, or pesticide use (Larsen et al., 2017).

The development of multifunctional land use and management requires new or better baseline data, including the identification, understanding and/or development of spatial data and information sources and technologies. Hence the following research and innovation activities should be prioritized:

- How land use and agricultural production systems influence emissions (GHG, N, P, etc.) from different soil and field types, cropping systems, fertilizer systems, etc.
- Monitoring protocols to fully document, monitor and detect climate, environment, and biodiversity specific to each land use element, as well as their biodiversity potential.
- 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.
- Breeding of novel high-yielding, resilient crop variants with increased N uptake efficiency, lower NO_2 emissions, and improved feeding quality to decrease downstream GHG emission.
- Updated and improved maps of land related properties, including soils, emissions, and biodiversity.
- Advanced precision technology and decision-support tools for optimizing land use and management.
- Predictive models for biogeochemical processes in mineral soils and wetlands, including the role of microbiomes and the effect of landscape structures and hydrological conditions on GHG emissions.
- Develop next generation technological filter solutions and sensors for monitoring and controlling concentrations and fluxes of nutrients, pollutants and other substances.
- Model effects of proposed solutions based on test data.
- Make cost efficiency analysis for the most likely implemented measures for the mitigation of emissions, nutrient loss, and biodiversity loss. The effect of proposed solutions on crop yield and crop quality.
- A regulatory framework for documentation of new technologies.
- Optimized legislation, regulation, and organization to ensure sustainable land use and management.

Measures applied for the various purposes need to 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 centers, such as Living Labs, are critical. This is needed, also because current knowledge is challenged from changing climatic conditions with more extreme rainfall and temperatures affecting emissions and nutrient losses (Olesen et al., 2011).

LAND USE
Across land use of organic and mineral soils, emission of CO_2 relates to the mineralisation of organic carbon and associated N_2O emissions (Abraha et al., 2018). For mineral soils, the importance of drainage status of mineral soils for GHG emissions, in particular N_2O, is not well understood. 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. There is a need to develop technologies and measures to allow cost-efficient rewetting with maximum GHG reductions, low environmental impact and supporting biodiversity (Zak et al., 2019). There is a need for development of filter-based solutions such as constructed wetlands and next-generation compact filters to protect the aquatic environment from N and P loads and to ensure nutrient recycling. Specific needs in relation to rewetting, wetlands and poorly drained mineral soils, as well as Technology Readiness Level (TRL) and Societal Readiness Level (SRL), are as follows:

- Knowledge basis for restoring 200,000 ha of former wetlands in the landscape for reduction of nutrient loadings, carbon sequestration and biodiversity hot spots (TRL=9, 2050 and SRL=7, 2030).
- 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 areas nationally 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/filters and at least 5,000 (TRL/SRL=9, 2030) and 10,000 (2050) saturated and intelligent buffer zones to reduce N and P loads with low costs and with enhancement of biodiversity.
- Development, formulation (TRL = 5, 2025), and testing (TRL = 7, 2027) of new compact filter structures and principles for N and P that allow for nutrient recycling.
- 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
In cropping systems, reduction of N_2O emissions from mineral and organic fertilizers, and crop residues will be prioritized. First, cropping systems should be more N efficient to prevent losses, including leaching and N_2O emission, and to enhance soil carbon sequestration. This will entail development of new fertilization schemes and technologies. Increased primary productivity is possible through temporal and spatial diversification of cropping systems, improved efforts to improve biotic and abiotic stress crop resilience, biomass production and resource utilisation (Tilman et al., 1997). This involves better use of the entire growing season with increased use of perennial crops, supporting biodiversity and enhancing productivity (Asbjørnsen et al., 2014; Englund et al., 2020). Resilience and diversification will minimize 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 improving 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 here to be seen in a circular perspective, where a larger part of the N and P nutrients are recovered from the landscape and in waste streams and then recycled as fertilizer 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 waste. These efforts support soil quality and soil health, thus, increasing resilience of the cropping systems to environmental stress. Topics required and associated TRL are:

- Disaggregated N_2O emission factors for fertilizer types (TRL=8), nitrification inhibitors and cultivation methods (TRL=8), revised model for predicting emissions from fertilization (TRL=7), and environmental risk assessment for nitrification inhibitors (TRL=9) (2025).
- Advanced modelling approach for predicting N_2O emissions from fertilization based on soil and environmental factors and fertilizer type (TRL=7, 2030).
- A 70% reduction in N_2O emissions from mineral and organic fertilizers through adoption of improved fertilizers and timing of fertilization documented through precision farming technologies (TRL/SRL=9, 2050).
- 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 to obtain greater resilience to environmental stress, improved 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 fertilizers 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
Land use also deals with landscape planning and governance, including afforestation, nature and biodiversity protection (Landis, 2017). 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, maximizing biodiversity within agricultural production systems, increased grazing by livestock, and implementation through transformation of incentives (subsidies) and legal frameworks for nature and agricultural management. Cropping systems can accommodate more biodiversity through diversified cropping systems, agro-environmental schemes that maximize biodiversity elements within agricultural production systems, and agricultural systems with complementary functional traits characterizing high biodiversity ecosystems that stimulate productivity and facilitate stability (Duru et al., 2015).

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. First, to plan the best available distribution of functions (agriculture, biodiversity protection, forestry, energy production, recreation, residence etc.) in landscapes. Second, to develop regulative measures and incentives that support the green transition in relation to both technological innovations, land distribution, and landscape management. Third, to establish effective institutions 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 transition. This involves considerations of how to reduce the increasing distance between humans and other species, as well as between consumers and the agricultural sector, and more biodiverse and mosaic landscape vegetation structures could be a way forward, where humans and livestock act as nature managers and conservers rather than as consumers and producers. This also involves discussions on the complexity of nature management and an understanding that some management practices, such as grazing, might be an asset when it comes to biodiversity but a problem from a climate change perspective.

Topics and TRL/SRL include:

- Establishment of methods for documenting ecosystem services and functions, including GHG, drinking water formation, nutrient loads to the aquatic environment, 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 prioritize 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).

Current challenges and gaps

TECHNOLOGICAL
A major challenge for tracking the mitigating effects is the lack of data and mapping of land attributes such as soil, water, carbon and biodiversity. This includes quantification of carbon disappearance rates on organic soils. There is also a lack of data on governing subsurface geological structures, the hydrological cycle, the related biogeochemical cycles and highly integrated modelling capabilities of water and nutrients flow and reduction. This further relates to the

need for novel sensor technologies, including remote sensing, for mapping of resources (C, N and P) and for mapping soil conditions relevant for determining GHG emissions under field conditions, in particular related to soil water content, porosity and carbon content.

Generally, modelling tools are necessary. Current models cannot accurately predict the influence of soil, climatic and management effects on factors such as GHG-emissions, C-sequestration and P-dynamics in restored wetlands, constructed wetlands and rewetted buffer zones as 'nature-based solutions', because we cannot quantify the processes and their intrinsic coupling between elements and to biota. Therefore, we need observatories that as Living Labs can be used as testing grounds. More emphasis should be on development of mechanistic modelling approaches.
There is a need to strengthen knowledge through a targeted effort that aims to quantify CO_2, CH_4 and N_2O emissions from peat soils in relation to the soil's content of organic C, water saturation, nitrogen status (C/N ratio) and pH. Especially the result of the tradeoff between reduced CO_2 emission and increased CH_4 emission upon rewetting remains highly uncertain due to lack of data. Further, we have a distinct lack of knowledge in relation to the emissions from the large areas of soils with 6-12% organic C. In addition, we need to understand how element cycles interact in wetlands and not at least the very critical and microbially controlled interactions between iron, nitrogen, carbon and phosphorus that strongly impact both GHG emission, C sequestration, iron (ochre) and phosphorus leaching.

There is also a great need to better predict the C and N cycle on mineral soils and the interaction of management with soil water content, in particular for N_2O emissions. It is important to note that mineral soils in general become wetter with increasing annual precipitation and hence that wetland soil areas extend over time. In this context is is relevant to expand the use of data-driven AI predictive models (neural networks) since these have shown the potential to do much better than more classical predictive models. Especially the rise of graph neural networks is very promising in this respect.

There is a need to improve the basic insight into the quantitative effect of manipulating plant metabolic processes on carbon and nitrogen cycling affecting GHG emissions, including what this means for plant breeding to lower N_2O emissions from agricultural fields. The long generation time for breeding of most plant species represents a major bottleneck for crop improvement, creating the need for technologies that accelerate crop development and generation turnover. Developing new kinds of crops — higher yield, more nutritious, drought- and disease-resistant — can take a decade or more using traditional breeding techniques. In the meantime, research efforts to uncover existing and designed gene variants are required for this development and accelerating implementation to allow these crop improvements. Subsequently, a combination of speed breeding and other state-of-the-art technologies, such as genomic selection and CRISPR gene editing, are promising strategies to accelerate the development of improved crops.

There are also considerable technological gaps when it comes to developing fertilizers with lower associated N_2O emissions, although some of these exist in the form of nitrification inhibitors. There are prospects for upgrading livestock manure and anaerobically digested biomasses and recycled crop residues thus to a large extent eliminating the need for external fertilizers. However, this requires new technologies that also focus on high efficiency and low losses of the N fertilizer products and high carbon retention of residual carbon compounds, e.g., through pyrolysis and production of biochar.

IMPLEMENTATION
Changes in land use are often complex processes, where the implementation of desirable changes becomes the bottleneck, and there is a need for smooth and speedy processes that are based on transparent regulations and have the necessary involvement of actors. Coordination of multiple, sometimes conflicting, goals across different policy instruments is needed in order to proceed efficiently. The municipalities in Denmark have no tools in the spatial planning procedures and no instruments to take active part in land redistribution and land consolation processes and these instruments are empirically needed to promote voluntariness and create benefits for the stakeholders involved. There is a need for simplification of the administrative process in the land distribution work. This can be done by merging the land distribution order with the cadastral update to an administrative act. Financing models and incentive structures must be built as well that make the land distribution attractive to the individual farmer.

Development and implementation of novel perennial and arable cropping systems that fulfill multiple objectives need to be adapted to the local context, in particular in terms of soil, climate and farming system. This requires local learning and experimentation, which can be achieved by linking research on novel cropping systems at research centers with on-farm experimentation that have the structure of living labs. There will also be the need to assist the implementation and upscaling of novel and more complex cropping and fertilization schemes with digital technologies to monitor and predict their effects on multiple sustainability indicators, and to use these experiences for further improving cropping systems and related technologies.

FINANCIAL
There is a need to investigate and develop new types of partnerships and funding models to ensure efficient and speedy changes in land use, including rewetting agricultural soils, afforestation and enhancing nature areas, which also involves the documentation and valuation of biodiversity effects.

Strongholds and potentials

The unique Danish stronghold is close collaboration between universities, industries and farmers ensuring rapid feedback and immediate implementation of new technologies. One example is the IFD-funded project SmartGrass, where a world-class breakthrough in image recognition of clover using machine learning allows optimized nitrogen supply to grass clover pastures, already implemented in online farmer decision support.

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, FieldSense). Denmark has strong science basis in biodiversity and nature restoration, and the use of novel technologies to monitor changes, and there are also companies working on these aspects (e.g., FaunaPhotonics, Rambøll, HedeDanmark). Further, Denmark has strong competences in mapping soil and hydrological conditions affecting environmental impacts as well as development of environmental technology including sensors, filters and machines (e.g., FOSS, Aarhus GeoInstruments, WSP, Veolia, Grundfos).

The annual financial needs for research and innovation are estimated at around 1.5 b 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 b DKK annually for the next couple of decades.

Concrete goals and key activities

2025: Modelling, screening and testing of promising technologies for reducing GHG emissions with preliminary cost-effective analysis carried out, preparing for full implementation. Better mapping of emission and nutrient flows to target measures. Start on mapping and use of microbial biomes in natural and restored wetlands. Development of predictive models for hydrological and biogeochemical processes in wetlands. Better, more compact retention technology including recycling (filter methodologies) for constructed wetlands. Better understanding of biodiversity requirements in agriculture. Better knowledge to support all themes. Extending current fields and areas under transformation or inclusion in transformative projects (changing cropping, changing wetland, etc.). Living Labs as national observatories established for continuous baseline data and demonstration facilities before large-scale implementation with documented valid solutions (proof of concept). Established pipeline for integrating national data and data platforms to decision support tools, assisting managers in optimal selection of treatments.

2030: Innovation and research activities have resulted in full implementation of existing technologies and 10-50% implementation of novel technologies, including scale-up of relevant new measures to reduce emissions, pesticides, and nutrient losses from agricultural fields. Improved products along catalog preparation on mitigation options (improved crop rotations, crop residue handling strategies etc.). Genotype design, genotype testing and genotype-to-phenotype prediction advanced. Concept for speedy land redistribution regime ready.

2050: Carbon neutrality of the agricultural landscape with reductions in nutrient loadings to aquatic ecosystems that will enable good ecological status and reestablishment of acceptable biodiversity in the landscape. The following specific targets are achieved:

- 70% reduction in N_2O emissions with reference to 1990
- More than 250,000 ha of low-lying soils have been restored as wetlands, and >10,000 nutrient filter constructs established along streams
- 50% of agricultural land converted to perennial cropping
- Offsetting GHG emissions by adding resilient carbon (e.g., biochar) to soils corresponding to 2-3 m tons CO_2.
- Replanting forests to enhance carbon uptake by 1.9 m tons/year over 100 years

This will go hand in hand with identification and integration of various data sources for the development, calibration, and validation of the models to monitor and verify progress towards the goals.

Impact on strategic goals and value creation

The optimised land use and management schemes will result in increased biomass production for sustaining agricultural feed and food production, as well as reduced GHG emissions, reduced pesticide use and leaching, reduced N and P loads to the aquatic environments and creation of 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 as well as development and implementation of new technologies. The greater productivity and reduced needs for external inputs in the cropping systems will improve profitability of these systems.

GREENHOUSE GAS EMISSIONS AND REDUCED NUTRIENT LOADS TO AQUATIC ENVIRONMENTS

It is estimated that all organic soil can be rewetted by 2050 and that this would reduce emissions by about 4.6 m tons CO_2-eq annually. The area rewetted and converted into wetlands will be larger than this, since it will also cover mineral soils. These reestablished wetlands in combination with constructed wetlands and other filters in the landscape have a major contribution to reducing N and P loads to the aquatic environments.

The emissions of N_2O from fertilizers and manures may be reduced by a minimum of 70% by 2050 through a combination of new fertilizers, use of nitrification inhibitors and cropping systems with better N use efficiencies and lower potential for N_2O hotspots. The potential for reducing N_2O emissions from ammonia volatilization, nitrate leaching and crop residues is estimated to be in the order of 30-40%. Nitrate leaching from the agricultural land will be reduced partly by converting some of this land to nature and forestry and partly by improved cropping systems and fertilization regimes. In particular use of perennial cropping systems and improved cover cropping has the potential to reduce nitrate leaching rates.

Soil carbon will be increased through use of perennial cropping systems, setting aside agricultural land for nature and through use of biochar as soil amendment. This will be supplemented by increased carbon storage in vegetation from afforestation of agricultural land. The estimated contributions of this by 2050 are in the order of 4-6 m tons CO_2 annually.

REDUCED PESTICIDE USE

Pesticide use will be reduced through changes in both cropping systems, plant breeding, use of plant microbiologicals and novel sensor and AI technologies supporting precision application of non-chemical agents to reduce chemical pesticide use. This should result in a 45% reduction in chemical pesticide use by 2030 and 90% by 2050. This will allow Denmark to meet the goals for pesticide use reductions stipulated in the Farm to Fork strategy and the EU 2030 Biodiversity strategy without compromising resource utilization.

RESILIENCE TO CLIMATIC CHANGE

Modelling tools to analyze impacts of weather extremes and how biodiverse cropping systems add resilience to extremes will benefit the agricultural sector, as well as local and national authorities, especially on how to tackle extreme weather events such as heavy rainfalls and prolonged droughts caused by climate change. This may support new insurance instruments as well as technologies for better managing hazards in crop and soil management, and the subsequent developed products may both be applied in Denmark as well as for export.

ENHANCED BIODIVERSITY

Targeting the strategic goals of enhancing biodiversity will only be possible with a new data-driven infrastructure to document progress in improving aspects of biodiversity through both land sharing and land sparing. Both aspects are considered in this roadmap and they should be considered to contribute to different functional aspects of biodiversity improvement.

VALUE CREATION

There are considerable economic benefits from increasing productivity of agricultural cropping systems. Thus, a 1% yield improvement in Danish cereals has a value of ~120 m DKK, and breeding along with changes in fertilization, crop protection and novel cropping systems has the potential to increase productivity by 30-50%. Further, the agricultural production economy may be improved for potentially up to 260,000 ha land if improved drainage systems are implemented, and if this is linked to increased retention of nutrients in the landscape allowing optimal crop production processes to take place. Improved nature value and biodiversty also have enormous potential to increase well-being of humans which is difficult to quantify the value of.

The quantification of ecosystem impacts will secure the basis for a certification system that will allow financing the change. It will also pinpoint focus areas for further research and for management optimization.

The largest part of the value creation will come from three pathways:

1. meeting sustainability targets within agricultural land use 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, production of clean drinking water, and tourism, and
3. export of technologies within plant breeding, crop and nutrient management/recycling, 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 (e.g., risk of losing nutrients and producing N_2O when renewing crops in perennial cropping systems or increasing risks of diseases and pests to spread with new cropping and planting systems),
5. low cost-effectiveness of measures (e.g., resilient cropping systems and novel management solutions),
6. incompatibility with current land use and agricultural systems, and
7. unwillingness among actors for a social and cultural transformation of sustainable green solutions.

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.

TRACK B **ANIMAL-BASED FOOD PRODUCTION**

Vision

The vision for this track is to identify, develop and implement activities, which will ensure production of the most sustainable animal-based food products in the world with a low GHG emission to accommodate and meet a growing worldwide demand for animal-based proteins and foods. A diet with a low carbon footprint 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. Documentation and sharing e.g., use of big data and technologies through an established common data platform collecting data from sensors and other sources, have 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:

- Minimum 50% reduction in direct methane emissions due to a reduced production of enteric methane (equivalent to 2.1 Mt of CO_2-eq.) (Nielsen et al., 2021) without compromising production, 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 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.
- 10% reduction in excretion of N from livestock production facilitating a 15% reduction in downstream ammonia and nitrous oxide emissions.
- 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 2.0 Mt of CO_2-eq (Nielsen et al., 2021).
- 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 (Kristensen & Weisbjerg, 2015). Approx. ¼ of this improvement is through improved management and precision livestock farming.
- In 2030 development of biorefining of green and blue biomasses will reduce import of protein to the conventional livestock sector by 30% (National Bioeconomy Panel, 2018)
- In 2030, 5% of the Danish animal protein production is from insects for food and feed.

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

- 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.
- In 2050 aqua culture and fish production is doubled in Denmark 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.

It is important to establish knowledge about consumer preferences and how to induce changes among consumers towards a sustainable diet with a low carbon footprint, including knowledge about consumer misconceptions about the impact of largely animal-based diets. Consumers are interested in tasty and nutritious food, and retailers only want to sell products where there is a clear consumer benefit. Therefore, new products that meet consumer demands and have a lower climate impact have been developed. Because Danish production is export-oriented, it is necessary to take consumer preferences on export markets into account, as well as high-value products in more extensive production systems.

Objective and goals

Several factors play a crucial role in achieving the overall goal for 2030 and 2050 on climate for the animal food system. The technical focus areas include identifying efficient nutritional, genetic, and microbial interventions that can drive a substantial reduction in GHG emission, particularly enteric methane from livestock, which accounts for 35% of the total greenhouse gas emissions from Danish agriculture. Morover, a significant improvent in animal feed will lead to improved N-efficiency and thereby reductions in climate impact of downstream methane, ammonia, nitrous oxide

Key activities and workstreams

Cli	Env	Inn	Nat	Barr	
				CFG	Methane and ammonia reduction (Livestock)
				CFG	Capturing methane and ammonia (Buildings and systems)
				CFG	Circular perspectives
				FGR	Management and precision livestock farming
				BFR	Alternative animal production systems

TABLE 7 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.

emissions and reduced N-leaching. Manure management and related technologies have an exceptional potential for contributing to reducing greenhouse and other biogenic gas emissions from animal-based food production while also contributing to fossil-free energy production and optimized nutrient utilization and cycling. The manure management chain involves livestock houses and external (outside) storage and contributes on the order of 1/4 of the total greenhouse gas emissions from agriculture in Denmark (Nielsen et al., 2021). It is also crucial to apply a chain approach and look beyond single technologies. A key objective therefore is to identify, combine, integrate, and implement compatible technologies and mitigation strategies that allow for ambitious reduction targets. This needs to be supplemented with a continuous development of new technologies that can be added to the suite of emerging mitigation measures.

This overall strategy is completely aligned with the aim of improving air quality and environmental pollution by reducing emissions of ammonia and other biogenic gases (e.g., VOC and H2S) from manure including fertilization. Circular recycling of carbon, nitrogen, phosphorus, and other minerals is key to the vision for a fossil- free and sustainable food production.

It is vital to obtain a good understanding of the production of different and new biomass sources as well as the bioprocessing of those. The nutritional value of different biomass sources and their possible use for different purposes is also needed. This requires a good collaboration with manufacturers and engineers developing biorefining processes coupled with competencies within cross-species animal nutrition and analytics.

Finally, novel technology must be implemented in low-emission production of invertebrates (molluscs, crustaceans, insects) and lower vertebrates (fish) securing a minimal effect on terrestrial and aquatic ecosystems. These sources are to be used as direct sources of raw material for food products but also as more sustainable sources of raw material for feed. Low-value waste products must be converted to high-value feed and thereby reduce the requirement for imported raw materials i.e., soy. The reduced effects on climate and environment and improved standard of biodiversity and reuse of waste must be documented for the 2030 and 2050 goals.

Current challenges and gaps

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.

Enteric methane from rumen fermentation is the largest individual source that accounts for 35% of total GHG emissions from Danish agriculture (Nielsen et al., 2021), and more than 50% of the on-farm carbon footprint of milk (T. Kristensen, Aarhus University, pers. comm., 2021). 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. 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. Such improvements in efficiency should be based on combining breeding and management (nutrition) improvements. This will require large-scale measurements at individual level and, possibly, new types of data such as measurements collected in slaughterhouses potentially using new technologies. Large-scale data will allow investigation of the role of genetics and the microbiome for efficiency.

Dietary interventions such as an optimized protein and amino acid supply for monogastric animals, and the use of diets high in fat, sugar and starch for ruminants may have both positive and negative effects on downstream emissions of nitrous oxide, ammonia, and methane, which could be employed for biogas production. Simultaneous process chain optimization might concurrently reduce enteric methane and increase biogas production. As a benefit the risk of reduced digestibility in the animal is no longer a constraint for ration formulation if biogas is included in emission calculations. Biogas production therefore requires a re-evaluation of the term "nutrient utilization", as optimal ration compositions and feeding levels might change, when the manure utilization in biogas plants is taken into account.

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. 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. 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. There is a need for developing alternative technologies for outdoor storage tanks. These should include alternative manure treatment systems, but treatment of controlled ventilation exhaust from covered tanks is another promising strategy. At high methane production, this could be combustion systems (flaring), whereas at lower methane levels, novel methane capture technologies have been suggested. These include, but are not limited to, new chemical oxidation processes (e.g., chlorine-atom reactors and catalytic processes) that need further research and development. A critical knowledge gap concerning nitrous oxide from manure storage also needs to be filled. Current data for Danish conditions indicate that nitrous oxide contributes <5% to climate forcing compared to methane, but systematic animal production-scale data are hardly available. In addition to emission data for nitrous oxide, potential effects of methane mitigation on nitrous oxide need to be investigated.

Apart from ventilated storage with optimized methane oxidation, methane capture technologies may also be considered for treatment of whole-farm ventilation exhaust or hybrid ventilation in dairy buildings. The significant challenges of this are related not only to obtaining efficient and high-capacity capture processes for treatment of vast volumes of air, but in the case of cattle production a transition towards mechanical ventilation (e.g., partial ventilation) is also needed. Nevertheless, there is a strong need to clarify feasibility, which should also consider animal health, energy consumption and productivity. Emerging agricultural air pollutants include volatile organic compounds (VOC) and sulfur compounds. Agriculture contributes significantly and possibly dominantly to national emissions of these compounds. Technologies with effects on methane and ammonia emissions will to some extent also reduce VOC and S emissions, but further data are needed to ensure this.

Dedicated efforts to control carbon turnover in the manure chain need to be associated with exploring carbon sequestration through biochar and novel potential means of stabilizing carbon. This requires further development and documentation of advanced technologies that can extract non-utilized carbon and treat it by e.g., pyrolysis. Integration with biogas production and manure separation processes is crucial and needs further research and innovation. The potential of this is significant since it will also lead to reduced emissions of nitrous oxide following manure application to agricultural soil. 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 compromise the welfare of the animals.

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 e.g., it is not allowed to use acidification with sulfuric acid or synthetic methane and nitrification inhibitors. 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. Increased use of bedding material for animal welfare leads to more slurry carbon. This may increase biogas production but may also lead to higher methane emissions, if not handled correctly.

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-economically feasible way. To get the highest valuable compounds and fractions out of the processing, the crops for biorefining such as grasses, clover, alfalfa, catch crops, and seaweed, need to be optimized with respect to composition, cultivation, harvesting techniques, logistics in connection with the process optimization of the biorefining process. Algae, seaweed, salt and drought tolerant plants and microorganisms also have potential for producing feed ingredients, eventually by utilizing or upgrading low-value side streams. For all biomasses, circularity, sustainability, climatic impact and a thorough chemical and biological evaluation of use of the products, as well as the in vivo documentation for their nutritional potential and value of the products, also in terms of health promotion, is necessary. Several interesting biomasses from various sources may contain naturally or following biorefining health promoting bioactive compounds that can reduce or eliminate the use of antibiotics. A major challenge in circular bioeconomy is often to pin out single business cases, as it is the utilization of all products and processes in the circle, that create the sustainable business.

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 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. Sensor processing with neural networks holds the potential to provide flexible solutions to a range of problems related to classification and support for precision livestock farming decisions. 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.

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. A high survival rate among production animals is needed to decrease the carbon footprint and improve health standards. Preharvest mortality represents a significant contribution to the carbon footprint and efficient methods to reduce mortality must be developed. Fish feeds represent the main carbon input to fish farm operations and optimization of feed ingredients and feed conversion rate is needed to reduce the carbon footprint and reduce contents of health impairing substances. Cultivation of mussels 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 and lack of technology for processing into commercial products.

Insect production may also 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. Insects are still not entirely ready to be used directly in human diets, partly due to lack of knowledge regarding establishing the nutritional value of insects in the context of human diets and nutritional requirements, Moreover, there is still a lack of new recipes using insects in combination with other products resulting in tasty and attractive meals to the consumers, which subsequently positions insects to be a suited replacement of terrestrial livestock meat. Despite unknowns and challenges insect production harbours great potential to supplement future sustainable protein production. This is aided by their ability to convert sidestreams and waste products into high quility protein and their fast generation time providing large potential for changing relavant traits through selective breeding.

Financial aspects

RESEARCH

The agri-food area has seen reductions in public funding sources, and research funding are increasingly dependent of private foundations. Further, many of the existing funding sources focus on developing technologies and business-ready research. Funding for dedicated research and innovation in agricultural GHG mitigation has until recently been relatively limited, both in relation to developing funda-

mental knowledge and data as well as process/technology development. Furthermore, there has been a deficit in social science research especially within the themes of efficient policy implementation and societal transitions.
There is also a need for financial support both for research and development within availability of biomasses, harvest techniques, logistics, process development, utilization and quality as feed for respective productions in relation to use of mainstream as well as side stream products.

DEMONSTRATION
The Danish animal production is challenged by the great investments in production facilities, low revenue per unit of produced product compared to other sectors and not least increasing annual variations on crop and feed production resulting from climate change. Thus, the farmers face difficulties in changing their production system for incorporation of new technologies, and the sector as a whole is challenged by the possible future introduction of climate taxes or "licenses-to-produce" without the appropriate instruments at hand.

There is a need for investment in R&D capacity buildup within this area, including integrated facilities that allow for research on a chain level as well as training of researchers and strengthening and expanding scientific and technological strongholds. There is a need for financial support to build and develop pilot plants, demo plants and finally upscaling to production plants.

COMMERCIALIZATION
When implementing the identified transition pathways for consumers and farmers, one barrier is to develop financial models that support this transition. This could be through financial incentive models. Achieving emission reductions and climate neutrality is only possible if economic incentives are implemented that allow for business development and emergence of companies targeting not only single technologies, but also comprehensive technology systems covering the chain.

Few and relatively small companies have targeted environmental technologies for agriculture in Denmark due to limited economic incentives and challenges in business development. There is a strong need to promote and motivate development of technological businesses targeting GHG mitigation. Furthermore, financial support is necessary for the documentation phase which can be very costly for small companies and may prevent the necessary commercialization of mitigation strategies.

Appropriate conditions must be guaranteed for the starting companies to be involved, as the individual companies will seldom be able to benefit economically from the whole circle. Regulative requirements can, however, force a commercial demand for certain products. Farmers are in general willing to produce crops for feed, but struggle with competition from low prices for imported soy or other feed ingredients.

Strongholds and potentials

Reaching the overall climate goal for the animal-based food production sector will require a multidisciplinary and circular approach and a close collaboration between researchers, product developers and industry from a wide range of disciplines and professions. Fortunately, the Danish agricultural and food system is among the world's most technologically advanced and with a good connectivity to applied science and policy development. Consortia need to include a broad stakeholder representation with relevant university partners, knowledge institutions, consumers, industry, regulatory bodies, farmers and commercial companies from the agriculture and food sector – both established as well as new start-ups.

In Denmark universities and other research and knowledge institutions have a very long tradition for cooperation about research into more efficient animal and food production. During recent years, efforts have been increasingly dedicated and significant experience built on how to improve production efficiency and implement strategies for optimized resource utilization for environmental and climate mitigation purposes in livestock production. The Danish livestock production has therefore positioned itself as world leading in production efficiency. Collaboration between e.g., universities and industry has helped ensuring that research and technology development has aimed at solutions that were practically and economically feasible.

Overall, the Danish research environments are go-to partners in the international research community. In summary Denmark's key stronghold positions for this track are:

- 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, such 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.
- Denmark has historically been among the leading countries within research in alternative animal production
- Danish research on mussel and oyster cultivation has for decades provided new knowledge and technology.
- Strong competences in research on consumer behavior, 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.

Key stakeholders incl. farmers, authorities, consumers, and organizations will demand generally accepted methods and protocols for documenting the effects of GHG-mitigating technologies. General trust in the mitigation strategy is a key factor for implementation.

Moreover, the Danish feed industry faces developing feed processing methods and feed additives that result in reduced methane production and N excretion by livestock, as feeding livestock will play a key role in the transition towards a more circular bioeconomy. Denmark also houses internationally prominent breeding organizations for both pigs and dairy cattle. Any advances made in animal genetics and breeding can efficiently be translated into improvements in practical animal breeding. Danish research on mussel and oyster cultivation has for decades provided knowledge and technology, and Denmark has a leading position in seed production.

POTENTIAL PARTNERS
A range of universities, research institutions and industry nationally and internationally will be relevant and potential partners in key research, innovation, and demonstration activities. Some examples are given below:

National universities: Aarhus University, Aalborg University, Danish Technical University, University of Copenhagen, University of Sothern Denmark, Roskilde University
International universities: Wageningen, INRA, KU Leuven, Utrecht University, University of Lleida, Cornell University

Institutions, organizations and authorities: GTS institutes, SEGES, Foreningen Muslingeerhvervet, Danish Agriculture & Food Council and Food & Biocluster Denmark, Danish Aquaculture

Industry: Danish Crown, Arla, Chr. Hansen, ENORM Biofactory, Dansk Insekt Automation, Protix, Protifarm, Wittrup Seafood, Blå Biomasse, Triple Nine, Vilsund Blue, Biomar, Aller Aqua, Vestjyllands Andel, DLG, Danish Agro, Biocover, JH Agro, N2-Applied, Permeco, Cirtech, GEA, Nature Energy, Bigadan, Lundsby Biogas, Frichs, Aquagreen, Gråkjær, Agrifarm, SKIOLD, Landia, Washpower, SKOV, DOL sensors, Munters, DACS, KJ Klimateknik, Rotor, Big Dutchman, Lely, AgroVision, RYK, Cloudfarms, IQinABox, Viking Genetics, DeLaval, Foss, DanBred, Danish Genetics

Concrete goals and key activities

Concrete key activities for animal-based food production to support reaching the overall goals have been identified so far as:

Until 2025:
METHANE AND AMMONIA REDUCTION (LIVESTOCK)
- Develop new methane mitigating feed additives and identify potential adverse trade-offs on animal health, animal welfare, production level and product quality of current and novel feed additives for livestock.
- Determine the role of microbial trophic interactions on methane emission, N-cycling and responsiveness to mitigation strategies.
- Identify the optimal strategy for use of fat as a methane mitigation tool in ruminants under practical conditions.
- Identify the optimal composition of the diet in order to minimize the total carbon footprint from enteric methane emission, downstream emissions and feed production.
- Validate new large-scale phenotypes for methane production, feed efficiency and longevity and associate these phenotypes with genetics and metagenome information as well as estimating genetic parameters for these traits and their correlation with the breeding goal traits.
- Understand the role of host genetics and intestinal microbiome and their interaction in methane emission.
- Develop models for genetic (genomic) evaluation for methane emission by combining genomic, metabolomics and microbiome information.
- Develop methods to utilize multi-omics data, known genetic loci along with large-scale methane phenotyping studies for selecting low-emitting animals for breeding.
- Determine the role of various feedstuffs, specific feedstuff components, and feed additives on small intestinal amino acid digestibility and post-absorptive amino acid utilization by monogastric livestock.
- Improve understanding of amino acid requirement in cows pending on lactation stage.

CIRCULAR PERSPECTIVES

- New biorefining plants operate to supply the organic sector with protein and feed within the areas of green biorefining of forages, and biorefining of blue biomasses as mussels and starfish.
- Closed or semi-closed recirculation system based on wind and solar energy.

MANAGEMENT AND PRECISION LIVESTOCK FARMING

- Proof of concept for monitoring of climate and environmental impact at barn and herd level
- Prototype of common data platform established
- Prototypes of automatic monitoring systems of body weight
- Prototypes of data-driven decision support tools
- Prototypes of early warning systems for diseases and undesired behavioral patterns
- Proof of concept for individual feeding of growing pigs and slaughter calves

ALTERNATIVE ANIMAL PRODUCTION SYSTEMS

- Introduce LTA species (mussel, oyster) as an integrated part of Danish meals and utilization of their byproducts as feed for animals
- Insects: Develop technology to support automized large-scale production facilities
- Insects: Establish nutrient recommendations allowing optimal feeding and resource utilization
- Insects: Utilize specialized insect species and develop specialized genetic strains targeted specific biomasses

Until 2030:

METHANE AND AMMONIA REDUCTION (LIVESTOCK)

- Identify the breeding goal, phenotype and metagenome for animals high in longevity and efficiency and low in emissions of GHG, thereby reducing the climate footprint per animal and per unit of product.
- Identify molecular patterns/biomarkers to predict response to methane mitigation early in life (e.g., calf, heifer, piglet).
- Identify and start the development of more potent feed additives that can potentially reduce enteric methane from both conventional and organic ruminants significantly.
- Identify and start the development of new feed additives that can be used as a hydrogen sink and thereby avoid potential negative effects on feed intake of methane mitigating feed additives.
- Determine the impact of phage therapy both against bacteria and methanogenic archaea on rumen/intestinal microbiome dynamics/ecology and hence methane emission.
- Identify feed additives and feed processing technologies that enhance small intestinal amino acid digestibility and post-absorptive amino acid utilization efficiency by monogastrics.
- Identify alternative feedstuffs for monogastrics that have high digestible amino content.
- Identify specific feedstuff components that enhance post-absorptive amino acid utilization efficiency.
- Improve understanding and utilization of rumen microbial protein synthesis in on-farm tools for feed planning for ruminants.
- Target protein allocation by phase feeding to improve N and feed efficiency
- Develop strategies (feed, additives, microbial modulation) that can modulate the microbial colonization in early life in a consistent reduction of methane emissions throughout animal life.
- Identify dietary strategies in both ruminants and monogastrics that can reduce downstream emissions related to manure management and N-leaching.

CAPTURING METHANE AND AMMONIA

- Selection, integration and implementation of mature technologies, including final development of technologies i.e., integrated approach involving farms, treatment facilities, biogas production and carbon sequestration
- Research and development into novel technologies and strategies i.e., frequent or immediate slurry discharge and acidification and novel manure treatment
- Alternative technologies for storage tanks
- Development of a system for carbon accounting and tracking in the manure management system
- Novel innovation stimulating urination in cattle; control of elimination in pigs through resource placement
- Integrated technology systems, including e.g., robot systems for complete slurry discharge, sensor integration and data utilization
- Further attention to and development of the potential of developing technologies for specific side streams with the objective of extracting valuable products i.e., post-fermentation extraction of recalcitrant lignin and treatment by e.g., hydrothermal liquefaction
- Development of tools and infrastructure needed for approval of technologies and documentation of the achieved objectives
- Research aimed at improving the fundamental understanding and modelling of carbon turnover processes in the whole chain, including biological, chemical and physical processes.

CIRCULAR PERSPECTIVES

- Optimization of sustainable biomass production
- Optimization of harvesting machinery
- Optimization of logistic challenges
- Optimization of biomass separation processes
- Optimization of nutritional quality and utilization for animal feed purposes - Document potentials and challenges as feeds for high producing animals
- Optimization of utilization of side streams
- Maximal recycling of carbon, nitrogen and minerals

MANAGEMENT AND PRECISION LIVESTOCK FARMING

- Included digitalization, automatization and robotic operations (where possible)
- Individual identification of cattle and pigs + Individual feeding and individual monitoring of feed intake in slaughter pigs
- Use of sensors for phenotyping in breeding programs
- Prototypes of drone-based sensor systems indoor and outdoor
- Common data platform in full operation
- Extensive use of sensor data
- Monitoring of climate and environmental impact at barn and herd level

ALTERNATIVE ANIMAL PRODUCTION SYSTEMS

- Reduce mortality in production systems to less than 1% during the production cycle
- Reuse 100% of the waste from fish production for primary and secondary feed production
- Introduce new composition of feed for improving FCR and reducing carbon footprint and health impairing substances
- Proteins from microalgae cultures fed by CO_2 captured from power plant emissions will represent highly effective methods to reduce carbon footprint and reuse waste
- Insects: Support consumer acceptance and secure availability of nutritional high-quality food products
- Insects: Surveys on prevalence of unwanted microorganisms in production environment and laboratory testing of infectivity to insects
- Insects: Gather information on risks using new substrates (former foodstuffs and catering waste) for insect feed

Until 2050:

METHANE AND AMMONIA REDUCTION (LIVESTOCK)

- Develop new feed additives for monogastrics effective in enhancing amino acid digestibility in the small intestine and improving the efficiency of utilization of absorbed amino acids.
- Implement early life feed additives that can manipulate the rumen microbial colonization in a consistent and favorable way after rumen development.
- Manipulate the rumen and intestinal monogastric microbiome (phages, CRISPR-Cas9, diet) to increase feed efficiency and decrease enteric methane production.

CAPTURING METHANE AND AMMONIA

- Methane capture technologies for treatment of farm ventilation (full or partial/hybrid) exhaust

MANAGEMENT AND PRECISION LIVESTOCK FARMING

- Data-intensive production concepts with decision support based on sustainability
- Automation by robots and actuator

Impact on the strategic goals and value creation

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. The global demand for animal-based food is high and will continue to be high in the future, and livestock is a prerequisite for the progress towards more circular agricultural production systems. Animals are 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. Denmark has the know-how and technological potential to be world leading in the development and marketing of technical solutions needed to achieve the required reductions in climate impact.

The livestock sector has been playing a key role in the supply chain from farm to fork, and for logical reasons the commitment of all actors is to assure a continuing food safety and food security for society. The interpretation of the concept of "Sustainable Livestock Production" varies among stakeholders; consumers may associate sustainability with animal health and welfare, whereas farmers may associate sustainability also with livelihood and economic aspects. However, environmental aspects of sustainability and GHG emissions related to climate impact and carbon footprint of products are important. The livestock sector contributes significantly to the economic value of the national exports and to the employment rate, especially in rural areas of the country where other types of jobs are scarce. Climate challenges are global and to avoid leakage and outsourcing of Danish jobs, it is essential that Danish innovations are reproducible to be implemented globally.

› Track B Animal-based food production

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. Providing new knowledge and technology will enable the selection and integration of cost-effective combinations of mitigation and management instruments. The key activities will also provide a capacity and resource buildup that will benefit the continuous development of cost-efficient technologies and strategies. If full-house methane capture technologies can be developed in the future and implemented post-2030, this has a tremendous potential for reducing methane emissions from both manure and animals. If successful, such technologies can be used to supplement other strategies. In principle, this could enable an overall (agriculture) emission reduction for methane of e.g., 70%. This is, however, considered a high-risk objective and the first milestone is to clarify the feasibility.

An increase in perennial grassland crops, in nitrogen fixing crops (legumes), and a concurrent decrease in annual crops like grain and corn silage (with increased utilisation of catch crops) will reduce nitrogen leaching, increase carbon sequestration in the soil, reduce use of pesticides with more than 90%, and if the forages are properly managed increase the number of pollinators. A further improvement of feed efficiency due to inclusion of marine biomass sources as feeds will reduce the terrestrial area required to produce a given amount of animal-based food. Thereby more land will be available for purposes other than animal production, and overall biodiversity can be increased on both national and global levels. Increased utilization of marine biomasses will also remove surplus nutrients from the aquatic environment and spare arable land. Within organic animal food production, the activities suggested will ensure that all animal food production in Denmark will be produced on local sustainable feed sources with a very low impact on environment and climate. In the longer run, the key activities will ensure conventional animal food production with a marked reduced environmental and climate impact. Fish production is at present the most resource economic and sustainable livestock production form with a low carbon footprint compared to other productions of animal-based foods, which is mainly due to fish having a good feed efficiency. Therefore, there is a large potential in improving fish production to achieve a climate neutral production system.

BUSINESS POTENTIAL
Pathways can identify key elements of value chains resulting in sustainable high-end animal food products resulting in increased long-term productivity and value creation in the full animal food system. Further, this represents a huge business potential as all countries are facing the same dilemma regarding transforming the animal food system towards a more sustainable path, and solutions are needed globally.

The prediction is that livestock will also play a key role in national and global food supply in the future, and implementation of more circular bioeconomy approaches calls for use of the specific advantages of both monogastric and ruminant-based livestock production systems. The requested significant reductions in emissions can be obtained by reducing the footprint per kg of product, and this will make Danish livestock production more competitive on an international market, and potentially create more jobs in the sector, when low climate footprint products can be capitalized in the future. These jobs and revenue will not only be generated within the primary production and downstream industries such as dairy and meat processing companies, but also in industries involved in the development of the new and efficient GHG mitigation technologies. This could for example be breeding companies, feed suppliers, and companies providing feed additives and precision livestock farming tools.

In Denmark there is also a strong industrial environment focusing on the development of feed additives and genetic improvements. This has up until now primarily been related to improvement in nutrient utilization and animal health, and to a much lower extent in relation to identification of feed additives modulating gut methanogens, development of breeding plans for low-emission animals or more efficient animals. Precision livestock farming tools have been aimed at ensuring production efficiency, while maintaining good animal health, animal welfare and healthy and safe products. However, the Danish research environments and expertise are on the highest international level and can thereby form the basis for new business cases in relation to developing, e.g., new feed additives, mitigating technologies and breeding plans for low-emission animals in combination with introduction of new low-emission feed resources.

Another example is the Danish production of turnkey ready fish production systems, which is at present significant, but it is expected that novel systems securing low emission levels will be highly competitive on the world market. Genetic breeding of disease-resistant production animals has a high business potential. At present Danish fish egg producers cover 10% of the world market, but with genetically improved products it is realistic to expect a 50% coverage in 2030. EU has identified aquaculture as a key pillar in future food supply and new green solutions will therefore have a large export potential in the EU and globally.

More local and climate-friendly animal-based food production is a competitive parameter, and it is at the same time important to be in the front of development to keep market shares on a more and more climate-competitive market, where low climate footprint can be capitalized. A dedicated effort will give Danish companies a head start compared to many other countries. This should motivate both upcoming and established companies towards business models aimed at emission mitigation, but it does require a business transition and a certain degree of risk-taking.

Risk management and alternatives

Achieving the results and impact from research related to livestock production is very dependent on access to state-of-the art facilities, development of on-farm facilities and further recruitment of highly skilled personnel and PhD-students. Allocation and access to financial resources will therefore need to be a priority. A risk of not being able to perform experiments because of the negative reputation and regulations is also present.

Use of feed additives that modulate the efficient rumen symbiosis may have adverse side-effects related to animal health and welfare and this must 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 is 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.

Relation to other tracks

Livestock production and efficiency is highly related to upstream (plant production and land use) and downstream effects (manure management and biogas production), and it is essential that sub-optimization in parts of the chain is avoided. Livestock production will be a core part of more circular agricultural food production systems in the future, due to the special properties of both ruminants and monogastric animals with respect to the use of side streams, byproducts, forages, and fibrous feeds. Hence, this track generally has relations to several other tracks in this publication.

There are obvious relations to the track on “Crosscutting Issues” with respect to accounting and documenting GHG emissions, integration of sensors and data management, regulation and incentives, co-production of renewable energy and more. Documentation is the foundations for implementing economic incentives and acceptability as fundamental drivers for profound technology implementation and new systematic approaches.

Nutrient-rich output from the manure management chain is used as organic fertilizer in plant production hence the relation to the track “Land use and management”. The quality of the output has substantial implications for the downstream processes and effects. The carbon content of manure influences significantly nitrous oxide emissions following land application. A manure management strategy with high focus on carbon control and biogas integration will lead to reduced nitrous oxide emissions in the fields. Thus, strategies that incorporate this additional benefit should receive high attention (e.g., biochar, separation). In addition, high nutrient retention needs to be prioritized in relation to this track which includes a focus on reducing ammonia emissions. Likewise, a manure output that leads to lower loss of ammonia after land application should be prioritized, e.g., manure with high infiltration in soil, which requires further research into effects and optimization of manure application methods.

Alternative proteins and circular uses of biomasses for feed and food draw synergies into the track “Biotechnology-based solutions and alternative protein sources”, where focus is also on developing other food ingredients from micro-organisms, algae etc. Functional properties of alternative food ingredients apply to both tracks, when developing green/alternative protein ingredients with attractive functional properties.

TRACK C **PLANT-BASED FOOD PRODUCTION**

2050 Vision for plant-based food production

By 2050 we have successfully achieved net-zero CO_2-eq emissions by completing the transition to a more plant-based food system, where most of our food is sourced from plants, where all unavoidable food loss and waste is upcycled or recycled, and where low-density livestock production is integrated into regenerative agricultural systems featuring perennial crops and trees with high potential for carbon sequestration. Healthy, tasty and gently processed plant-based food products made from protein crops, specialty crops and other high-value crops cultivated by Danish farmers are being supplied for the domestic market and exported to the European and global market, thereby contributing significantly to substituting the consumption of meat with plant-based food. With less European and global land required for producing feed, all organic soils have been restored and trees have been planted on available cropland, sequestering carbon and making more space for nature, and thereby contributing to turning 30% of land in Europe into protected areas. Biofertilizers, biological control and plant biologicals have replaced chemical fertilizers and pesticides to improve water quality and increase biodiversity. New and improved traditional breeding technologies, better management practices, artificial intelligence (AI) and robotics have been applied together with renewable energy for agriculture and food processing, upcycling, and sustainable processing, to increase the efficiency of agriculture and food production. Farmers and food sector companies are generating most of their profit and employment based on a high demand for sustainable and healthy plant-based food on the global market.

2030 Vision for plant-based food production

By 2030 we have made significant progress towards a more plant-based food system where more than half of the protein consumed by humans is sourced from plants, and where food crops and plant-based food products grown and manufactured in Denmark have partially replaced European and global production and consumption of feed crops and animal-based food. This has made it possible to significantly reduce European and global methane emissions and nitrous oxide emissions from livestock and agricultural soils. With less European and global land required for producing feed it has been possible to restore organic soils and start planting trees on available agricultural land. Coupled with an increasing use of technologies for increasing the efficiency of agriculture and food production, this has resulted in reduction of global GHG emissions corresponding to 50% of the GHG emissions from Danish agriculture. Pressures on the aquatic and marine environment caused by erosion and leaching is decreasing and the risk and use of pesticides has been reduced by 50%, reversing the decline of pollinators. Farmers and food sector companies are generating a significant part of their profit and employment from the increasing global market for food crops and plant-based food products.

Objectives and goals

One road to reduce GHG emissions, increase biodiversity, and lessen the impact on the environment is to ensure a sustainable and just transition towards more plant-based food production and consumption. Several technologies, research areas and strategies need to be utilized by establishing multi-stakeholder collaboration between all relevant actors in the food value chain from farmers to consumers. In order to seize the opportunity for Denmark to become a global first mover in plant-based food production, we need to revitalize the Danish cooperative movement and strengthen existing innovation environments to develop new technologies and bring sustainable production methods and competencies to the next level.

Deep physiological phenotyping, new breeding technologies, advanced propagation methods and efficient management practices need to be developed for optimizing breeding and cultivation of a diverse range of existing crops, novel crops and newly domesticated plant species, that are selected for their potential as raw materials and ingredients for unprocessed and processed plant-based food products. Breeding should target optimized nutritional, functional and sensory characteristics, and the development of high yielding and high-quality annual and perennial crops that are more robust and resilient towards abiotic and biotic stress. Cultivation should target the development of resource-efficient management practices for conventional, organic and controlled environment agriculture (CEA), while also maximizing profits and minimizing environmental impacts. Plant biologicals based on microbes, plants, algae, and seaweed should replace chemically synthesized pesticides and growth regulators. Bio-based fertilizers from renewable and recycled resources should replace conventional fertilizers to maintain or increase crop yield by improving nutrient uptake, plant health and crop resilience towards extreme climate conditions. Food crop production should be combined with low-density livestock production in regenerative and economically viable farming systems featuring perennial crops, vertical farming, intercropping, and agroforestry with high potential for carbon sequestration, and provision of other ecosystem services, including overall greenhouse gas (GHG) mitigation, biodiversity conservation, watershed protection and soil health maintenance.

Key activities and workstreams

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

TABLE 8 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.

Upcycling and recycling should be applied to upgrade feed to food by producing food ingredients for direct human consumption (e.g., grass and rapeseed protein), and secure upcycling of side streams for feed and other purposes, while also integrating the production with bioenergy to minimize waste. AI and robotics should be applied to develop autonomous fossil-free robots that can effectively perform a range of operations on high-value crops, including primary, post-harvest and processing operations. New sustainable processing of raw materials, including fermentation, should be applied to transform plant materials into ingredients, or intermediate semi-finished products with high microbial stability, techno-functionality, and nutritional value. This will support the development of a wide range of high quality and sustainable plant-based food products covering the entire spectrum from unprocessed to more processed products that can cover all nutritional needs (e.g., essential amino acids and fatty acids, vitamins D and B12, calcium, zinc and iron), meet different consumer preferences and expectations with respect to unique sensorial attributes (texture, flavor etc.), convenience and price level, and ensure food safety by overcoming unwanted natural compounds (anti-nutritional, allergic, toxic). Large scale consumer dietary shift should be triggered by holistic approaches to behavior change. This means acknowledging cultural differences and that individual awareness and information availability is important for making informed decisions. Different consumer segments have different preferences (e.g., high quality or low price), and therefore the choice context needs to be designed in such a way so that the 'sustainable choice is always the easy choice' facilitated by social norm shifts, as well as bold market and policy instruments including legislative action. When all factors of influence work towards change, societal tipping points in which large segments of citizens radically alter food consumption and food habits are more likely, this way actively engaging consumers in making the necessary pull for a transition.

Methods for assessing the environmental, social, health and economic impacts of more plant-based food production and consumption should be developed for the global, national, corporate, farm and product level. The assessment methods should apply a life cycle perspective and include domestic and foreign material flows and impacts, along with economic equilibrium models that allow both absolute assessments and relative assessments. The results of the impact assessments should be used to guide research, innovation, farm management, business practices and consumer behavior. Viable transition pathways for overcoming existing barriers and contributing to achieving a more plant-based food production system should be identified, tested and scaled by co-creating actionable knowledge throughout the food value chain, and by learning from existing research and experience on food system transitions and real-world, collaborative testing and scaling of activities that turn vicious (self-defeating) into virtuous (self-reinforcing) transition cycles. The potential of private regulatory schemes and scaling up niche public policy initiatives at the national level to become transition drivers, should be investigated and exploited. Options for applying the experiences with public and private demand-side policy and related governance arrangements in a transformation of the Common Agricultural Policy (CAP) post-2030 to a sustainable food policy assisting the transformation and maintenance of sustainable farm practices, processing, distribution and consumption should be explored. Business models that competitively, more sustainably, and resource efficiently, can address barriers related to plant-based food production and customer requirements, should be developed and tested specifically to scale for maximum impact related to both environment and international business success, and to base the development on a clear strategy for financing.

Current challenges and gaps

TECHNOLOGICAL

Deployment of transition pathways for more plant-based food production and consumption depends on a wide range of economic, social, and institutional factors, and further development of technologies for producing crops, raw materials and plant-based food products requires further incentivization.

Current challenges and gaps within the plant-based value chain are i) weak distribution links, especially between farmers and food manufacturers, ii) lack of on-farm or local facilities for storage, pre-treatment and processing of crops and raw materials, iii) no large scale pilot sites/biorefinery/commercial production facilities for upscaling production, iv) lack of collaborative test-facilities, where breeders, farmers, knowledge and innovation institutions, food manufacturers and food service providers can work together, v) insufficient documentation and certification of food safety, traceability, life cycle analysis and sustainability, vi) inadequate utilization of raw materials and exploitation of residues/byproducts, vii) need for a united digital platform for communication between actors in the value chain and dissemination of 'the sustainable journey' from farm to fork, e.g. via a QR code on the food packaging.

With respect to breeding and propagation there is a need to integrate information from crop physiology, quality parameters of raw plant material, phenomics, genomics and other omics technologies in breeding programs. New and traditional breeding technologies should be applied beyond the model species and varieties, and high throughput phenotyping, genomics, and use of other high throughput omics technologies should be used to deconstruct the Genotype x Environment interactions for phenotyping traits of climate resilience.

With respect to crop cultivation, we lack knowledge on how to grow existing and novel crops targeted for human consumption and selected for their nutritional, functional and sensory characteristics. Furthermore, we lack knowledge on how to develop conventional and organic controlled-environment agriculture (CEA), stockless food crop production and mixed food crop and low-density livestock production in climate neutral and regenerative farming systems, that are both profitable and scalable under Danish soil and climatic conditions. There is a need for developing autonomous robots that can operate with a high degree of safety without human intervention as well as collaborative robots that operate in collaboration with humans and other robots. AI-based perception techniques and crop analyses that combine high-resolution sensors, chemical sensors and high-quality satellite data should be developed, and digital twins for agricultural robots, and high-value crops should be created to optimize production and processing of crops and raw materials.

Progress in the implementation of plant biologicals is currently hampered by lack of knowledge on the mechanisms shaping microbiome composition and functioning. There is an urgent need for more basic research on the interaction of biological products with the native microbiome, and efficient high throughput screening systems that identify suitable biologicals adapted to the relevant environmental conditions.

With respect to upcycling and recycling there is a lack of sustainable chemical process innovation for efficient separation and purification of food ingredients, efficient nutrient recovery and wastewater technology, and efficient methods for bioenergy production. Large-scale processing of plant-based raw materials is currently limited to few crops, mainly cereals, oilseeds, fruits and vegetables. Limited knowledge is available of the complexity of plant proteins, to support the production and optimization of protein-rich ingredients to replace animal proteins, and current industrial practices of isolating and concentrating plant proteins into food components generate significant amounts of waste. Novel approaches based on enzymes or fermentation technologies are needed for gentler treatment of raw materials and improving extraction processes. Multi-level analytics and process analytical technologies are needed to improve product and process performance. Whereas the overall health benefits of a more plant-based diet is well documented, there are still challenges with respect to developing sustainable and healthy plant-based food products since a) plants generally lack or provide little of some important nutrients, e.g., essential amino acids, polyunsaturated fatty acids, B12, vitamin D, zinc, and iron, b) the functionality of plant-based ingredients are different from animal-based ingredients, c) plant constituents are very different and, in many cases, difficult to digest and take up for humans (e.g. cellulose) compared to animal-based foods, d) assessment of the sustainability of a specific diet requires that all nutritional needs are taken into account, e) nutrient uptake is dependent on specific plant food structure and the interaction between different components in a food product, f) humans' nutritional needs are age dependent.

With respect to consumer behavior and dietary change, there is a need to scale up the production to a size that will make it possible to pay a fair price to agricultural producers while keeping the price for consumers competitive. There is also a need to meet new demands for clean label, lightly processed nutrient-rich plant-based foods, and dietary behavior change requires improved methods for assessing actual food consumption change and dietary behavior. In addition, large-scale behavioral transitions require the application of methods for developing active participatory citizen engagement and co-creation to achieve ownership of the change (e.g., living labs, citizen science). A major challenge for impact assessment is the time delay from changes in public regulation to changes in business practices and consumer behavior, to changes in pressures on the environment and finally to changes in the state of the environment. There is a need for developing methods based on the principles of technology assessment and systems thinking that enable assessment of potential and actual changes in impact from changes in agricultural and food manufacturing systems, including the impact from the utilization of waste and side streams, and the impact on nutrient cycling, both as ex ante assessments during innovation and as ex post assessments after a certain method, technology or social practice has been developed and implemented. Greenhouse gas accounting must contribute to achieving the climate objectives and compare the climate impact of different dietary patterns and related farming systems. This includes assessing the carbon opportunity cost and gains given the impact on the potential for carbon sequestration through ecosystem restoration. Multi-criteria sustainability assessment for the farm and product level needs to be developed and integrated with farm data and operational support tools. Development of methods for assessing biodiversity is a challenge because there are controversies between different approaches for assessing changes in the use of biomass. The impact on human health can be assessed as part of national dietary studies, but these studies are not conducted so frequently and are not assessing the actual impact on health. Economic impacts, including impacts from changes in employment, can be assessed with partial and general equilibrium models, but these models need to be adapted and better linked with models accounting for the environmental impacts of economic activities. Business plans need to address technological challenges related to primary production and development of circular waste value chains with high degree of circular economics, processing methods to ensure the desired quality, structure, nutrition, and taste as well as product development and agile logistics for distribution.

IMPLEMENTATION

A variety of farm-level uncertainties, mal-aligned consumer habits, market designs, (dis-)incentives, and counterproductive regulatory frameworks pose major challenges for implementing the innovation, diffusion, and scaling required for a transition towards a more plant-based food system, and there is a need for real-world experimentation and knowledge acquisition on how to overcome such barriers through the generation of transition pathways. Up until now public policies and regulatory frameworks for governing the food system have been strongly producer-oriented and focused primarily on income support, although provision of public goods has been required for obtaining farm payments over the last two decades. To transform the food system so that food production and consumption become more plant-based and sustainable, there is an urgent need to analyze the potential for introducing demand-side policies and governance arrangements. Such analyses should consider the political barriers to policy change which are rooted in decision-making structures in the EU and national agricultural policy making.

The plant-based food value chain is fragmented and there is a lack of collaboration, communication, and interrelation between actors. Commercial cooperatives for the animal-based food market are well established and highly successful, but they are not established for the plant-based food market, and this creates a critical gap in the value chain and an urgent need to establish sustainable sales channels, cooperatives or other collaboration models that are supporting value creation at the farm level and ensuring that a fair price is paid to the farmer. Currently, the demand for raw materials is not high enough to make food crop production profitable for Danish farmers, and there is a need to link the farmer with the rest of the value chain, including both local, regional and global food supply chains. A big challenge for implementing new breeding technologies is that most of the agronomical important traits in crops are complex traits with strong environmental interaction. Further development of methods for complex traits such as genomic selection and multi-omics prediction is needed, together with phenotyping on both the molecular and on whole plant level to identify biosignatures, while utilizing genetic diversity as an important resource to find useful traits both from ex and in situ collections. In order to ensure reliable sourcing of suitable raw materials for unprocessed and processed plant-based food products, we need to test different spatial and temporal cropping strategies for conventional and organic food crop production, we need multi-actor interactions to bridge the gap between science and practice, and we need on-farm demonstration of different soil, crop, nutrient, water and light management practices for stockless conventional and organic food crop systems, and regenerative farming systems combining food crop production with low-density livestock production. Due to a lack of efficacy data, standardized products, and clear procedures for approval, the implementation of plant biologicals is currently low. Furthermore, there is currently limited knowledge and no models to predict the environmental fate and impact of biologicals. Such studies and models should be developed to respond to public concerns and making the technology safe. Successful implementation of AI and robotics requires the development of communication infrastructure with open standards, exploiting the accurate localization offered by the GALILEO global navigation satellite system, electrification/alternative fuel sources and legislation allowing fully autonomous systems to operate, both for air-based and land-based robots. Implementation of gentle processing of raw materials requires the establishment of pilot plant infrastructures, where approaches and equipment for extraction, fractionation, functionalization, stabilization, and quality assessment of protein-rich ingredients from plant raw materials or their side streams can be tested. Due to the high complexity of plant-based materials, large experimental facilities combined with high throughput analysis, data sampling, predictive modelling and AI/ML are needed for enabling fast analyses and screening of specific plant material subjected to a range of processing conditions and treatments in order to develop ingredients for new plant-based food products with desirable sensory and nutritional qualities.

Human intervention studies are needed to assess the effect of more plant-based diet on appetite, food intake, body weight, and important risk factors for non-communicable diseases (e.g., type-2 diabetes, cardiovascular disease) as well as tolerability, acceptability, safety, and allergenicity. Dietary guidelines and nutrition policies have not been enough to achieve dietary change. Consumer behavior and behavior transformation theories as well as consumer research show that consumer-citizens are more likely to change their behavior when most or all factors of influence (and not information provision alone) provide a reason, nudge, push and pull to do so. Thus, it is important that there is individual awareness and information, but also that social norms among peers and in society overall are supportive, that it is easy and attractive to change, one has the capacity and opportunity to do so, and the process of change is characterized by positive feedback.
With respect to impact assessment the challenges for implementation are a consensus on LCA approaches (attributional, consequential and hybrid) and the use of the developed impact assessment methods as tools for accounting and as tools for guiding research, innovation, business practices and consumer behavior with full transparency and traceability. Recent controversies about e.g., assessment of use of fertilizer, use of pesticides, and use of biomass as energy resource, show the importance of building assessment and governance schemes, which are transparent with full public access to data and assessments, and are deliberative democratic by involving actors from research, public authorities, and stakeholder organizations in their development, use and evaluation. Implementation of business plans needs to consider the transition from low-value feed to high-value food production and value chains optimized for climate and adapted to consumer demand and enable the transformation of current business models and the development and scaling of new business models.

FINANCIAL
There is a clear and present need for further private-public financing towards research, innovation, product development and implementation activities to support the transition towards a more plant-based food system and enable the Danish society to overcome the barriers and fulfill its potential to become world-leading in fast-growing plant-based food value chains. As the market grows, margins threaten to go down, meaning that continuous investments, research, and innovation are needed to stay on top of the high-end, high-quality part of the value chain. At present, such investment schemes remain to be fully worked out and should include private and public investments in research relating to behavioral, legal, institutional and economic aspects of transitional processes. Fair pricing throughout the value chain and the development of new and innovative collaboration models are critical factors to unify the plant-based food value chains and initiating a transition towards sustainable plant-based food production. The demand for raw materials and novel processing of plant-based foods is increasing, but unfortunately, the demand is not yet strong enough for the established distribution/cooperative systems to enter the market. Hence, further funding aimed at research and development activities that can fill the current gaps in the value chain, improve the taste and quality of processed products and improve efficiency of the production and utilization of waste, side streams and byproducts is needed in the coming 5-10 years. There will be a need to transfer basic research for pre-breeding and the development of propagation techniques to the more applied research to close in on the gap to implementation. Applied research and development to optimize soil, crop, nutrient, water and light management as well as circularity in CEA, stockless conventional and organic food crop systems and regenerative agriculture farming systems will require funding from national and EU research and innovation programs (IFD and HE) coupled with co-funding from private companies. Screening of existing and novel crops, on-farm demonstration and scaling of stockless food crop systems and regenerative farming systems will require funding from national demonstration programs (GUDP) coupled with substantial cofounding from private companies. Especially for the development of regenerative farming systems there is a need for calls that are not entirely focusing on business potential, but also on societal and environmental benefits. Alternatively, the implementation of a payment for environmental services (PES) scheme, e.g., CO_2-sequestration, at the national or EU level could provide incentives for the development of more regenerative farming systems.

Costs to cover research on technical challenges and cost-competitiveness of upcycling and recycling and funding for safety assessments, product development, and development of IT platforms will require partial public funding through IFD and GUDP, whereas initial production and upscaling, including implementation of technologies will be covered mainly by private investments. Development of AI and robotics towards 2030 can be done in research projects co-funded with commercial companies. The implementation of robot and drone technologies towards 2030 will be funded both by large companies and smaller startups. With respect to the implementation of plant biologicals, a lengthy and often costly approval process is a barrier for small and medium-sized companies targeting the Danish and European market. The plant-based ingredients market is competitive and fragmented and despite large potential, limited production is done in Denmark. Most of the manufacturers are building strategic collaborations to develop methods for processing of raw materials and new plant-based food products, as significant technical challenges regarding functionality, taste and nutritional value of these ingredients are still unsolved. The sector lacks successful SMEs in the food processing area that can explore the possibilities within plant-based food and inspire the big players in the market, and large investments are needed to speed up the development of sustainable and innovative processes, equipment, cultures and analyticals for production of plant-based ingredients and plant-based food products from lab-scale to pilot and industrial scale. There is a need for more in-depth knowledge and experimentation on overcoming the barriers and using the drivers of behavior change in synergy and over time, to scale up and accelerate the dietary transition. However, such research is expensive. Consumer-citizen research of larger scale, longer timeframe, with real-time digital data acquisition methods, and of experimentation/intervention methodology is needed. Integration of consumer research in large population studies (e.g., epidemiological studies, cohorts, national surveys) should be encouraged. The agro-food area has seen reduced public funding for research and innovation and despite recent interest from private foundations, funding lags considerably behind. New incentive instruments may attract sustainable finance for implementation efforts as green investments become more transparent and less risky.

For impact assessment to play a role in innovation and governance of plant-based food production and consumption, economic resources need to be allocated towards the development of methods and use of data in national accounting that can be included in e.g., the national green account managed by Statistics Denmark. Furthermore, resources are necessary for research in the actual role of impact assessment in innovation and governance. There are significant financial challenges associated with attracting both seed and venture capital for food industry innovation (low profitability and scalability difficulties), funding to cover prototyping, testing and initial production, and research gaps should be financed by national and international funding. New investors in plant-based value chains should be considered, including crowdfunding and co-operative funding. Industry investments from large industry players could be based on high TRL/SRL and transformational strategies to 'go green'.

Strongholds and potentials

ACTORS
The proposed activities will involve the entire research, innovation and implementation ecosystem: Universities, GTS, and the entire value chain in the private sector: farmers and their suppliers, the food industry and their suppliers, the retail sector and consumers and the stakeholder organizations for farmers, businesses, employees, consumers and citizens, horticulturalist organizations, advisory services, breeding companies, energy suppliers, recycling and waste contractors and NGOs focusing on agriculture, food, climate and environment.

DESCRIPTION OF RESEARCH AND TECHNOLOGY POSITION
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 agricultural, nutrition, and food research and innovation (R&I). This enables us to support, foster, and accelerate new plant-based value chains that are today in an early, emerging stage. Denmark has strongholds in the research areas needed to support the strategic climate goals and position Denmark 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 behavior, food consumption and demand. Denmark is in a unique position due to its dietary guidelines (Fødevarestyrelsen, 2021) 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 prioritized plant-based food, and this needs to change to mitigate the risk of Denmark losing this

big commercial opportunity and to 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 and improved traditional breeding and propagation technologies, new food crops and farming systems, plant biologicals and AI & robotics. As well as already established Danish strongholds such as upcycling and recycling, sustainable processing of raw materials and food production further into the plant-based food sector. Denmark has one of the most advanced processing chains for meat and dairy products in the world, which is based on a long and proud tradition for cooperative systems, and the animal-based industry holds valuable experience and know-how, that the plant-based food system could benefit from. We also have significant strongholds and potentials within organic food production, clean label, and pure raw materials, and therefore also the potential to achieve a strong market position in plant-based foods. At the regulatory level, the National Danish Council on Climate Change advising the Danish Government considers a transition towards a more plant-based food production system vital for achieving the national climate target and achieving a sustainable Danish food system. Danish farmers and horticulturalists are highly motivated for implementing new knowledge and optimizing the management of crops, nutrients, water, CO_2 and light. There is a huge potential for upgrading different agro-industrial side streams into novel food types, by different innovative means, where Denmark is well positioned. This involves upgrading from feed to food, utilizing side streams for food, utilization of side streams for bioenergy and minimizing waste; supply chain and logistics aspects. There is a strong, scientific cluster in Denmark, and publications in plant, soil, agronomy and crop sciences show that the main universities are cited 60-70% more than the global average, and they are placed in the top regarding co-publishing with industry (IRIS Group, 2018). The universities are recognized for competences in food research in areas such as: processing, equipment design, food safety, fermentation, starter cultures, enzymes, chemistry, technological functionality, sensory quality and consumer perception, analytics, processing, AI and robotic manipulators. The Danish research environment is also well underway to becoming world-leading within plant biologicals, plant performances, breeding technologies, new foods and farming systems. The academic partners, together with DTI, offer a technological stronghold with theoretical and practical knowledge and experience on protein extraction, purification, processing and characterization, allowing companies to collaborate on the development of and gaining access to advanced pilot-scale equipment or sophisticated analytical tools. Added to this is a strong interdisciplinary tradition of looking into barriers, potentials, drivers, measures, collaboration, value chains, impact assessment, business plans and financing.

EXAMPLES OF POTENTIAL PARTNERS

Danish universities: UCPH, DTU, AU, SDU, AAU, RUC; CBS as well as GTSs

International universities: Wageningen University & Research, Swedish University of Agricultural Sciences, Heidelberg University, Humboldt University of Berlin, National University of Singapore, University of Hohenheim, University of Lincoln (UK), Agricultural University of Athens (Greece), Copernicus Institute of Sustainable Development Utrecht

Institutions, organizations and authorities: SEGES, Food & Bio Cluster Denmark, Plantebranchen, Global Food Standards Initiative (GFSI) Europe, Danish Standards, DANAK – Danish Accreditation Fund, The Veterinary and Food Administration, Danish Agriculture & Food Council, Confederation of Danish Industry, the Consumer Council, the Society for Nature Conservation,, National Danish Council on Climate Change, Ministry of Agriculture, DVA Frej, CONCITO, Danish Vegetarian Association, Ecological national association, Plantbased Knowledge Center. Citizens are through NGOs like Forbrugerrådet Tænk, Friends of the Earth Denmark (NOAH) and Danish Society for Nature Conservation (DN)

Industry (examples): Chr. Hansen, Novozymes, KMC, IFF, CP Kelco, Hamlet Protein, Arla Foods, Cosucra, Organic Plant Protein, Vestkorn, NISCO, Crispy Food Nordic, Agrain, Plantmade, NatuRem Bioscience, Nordic Seed, Sejet plant breeding, Dagrofa, DLG, Danish Agro, Meelunie, DLF, Langholt, Crispy Food, Nakskov Mills, Triple A, Dragsbæk/Naturli A/S, Axel Månsson A/S, Nordic Harvest, Nextfood, Nabo Farm, Tvedmose, Bygaard, Beyond Coffee, Meyers, Simple Feast, Pure Dansk, Møllerup Gods, Kragerup Gods, Danish Crown, Danisco-DuPont, Dryk, GEA, SPX, SiccaDania, MMS, Tetra Pak, Sani membranes, Aquapourin, FOSS, Grundfos, Videometer, IH Foods, Thise, Lantmannen, Orkla Foods (Naturli), Planteslagterne, Simple Feast, Easis, LikeMeat Nordic, COOP Denmark, Salling Group, Danespo, Langholt, Hamlet Protein, Triple A, Nordic Sugar AgroIntelli, FieldSense, Conpleks ApS, Danfoss, AGCO, John Deere, FarmingRevolution GmbH (Bosch), Farmdroid ApS, FOSS, Vector.as, Thise, IFF, Biorefine.dk, Viventes, Naturmælk, and new start-up companies.

Concrete goals and key activities

Concrete goals towards 2025, 2030 and 2050 have been defined for each topic along with key measures and activities to support reaching the goals. The list of goals and key activities can be found as a list at the end of the chapter.

Impact on the strategic goals and value creation

EXPECTED IMPACT OF KEY ACTIVITIES

Establishing multi-stakeholder collaboration between all relevant actors, revitalizing the Danish cooperative movement and strengthening the existing innovation environments are expected to build a strong and sustainable plant-based food value chain that will become a new position of strength for the Danish food sector. It will ensure a fair price for the farmer and improve overall profitability, while optimizing the production of locally produced raw materials, and increasing the availability of tasty, safe, healthy, and sustainable plant-based food. This will provide incentives for both farmers and consumers to change their behavior, in accordance with the national GHG emission reduction targets and the new healthy and sustainable dietary guidelines. Both climate, environment, biodiversity, public health, and economy will benefit from the combined impact of the key activities resulting in a successful transition towards more plant-based food production and consumption. New breeding technologies, crop cultivation methods and farming systems supported by plant biologicals, AI and robotics are expected to i) result in the optimization of the cultivation of a diverse range of existing and novel crops with beneficial nutritional, functional and sensory characteristics, ii) the development of new and resource use efficient management practices for conventional, organic and controlled-environment agriculture targeted towards producing food crops for human consumption, and iii) the achievement of highly productive and climate neutral or climate negative food crop production systems with or without integrated low-density livestock production. A shift from animal-based agriculture to plant-based agriculture with integrated upcycling and recycling where feed is upgraded to food with efficient use of side streams, will lead to a significantly lower land and water use, resulting in reduced environmental footprint and GHG emissions. The development and design of novel sustainable processing of raw materials using sensor, robot, and AI technologies will contribute to reducing waste and improving circularity, providing new plant-based ingredients and support the development of new plant-based food products with export potential and benefits for both climate, biodiversity, and health.

Research on consumer preferences, behavior change, transition pathways and societal tipping points and other key activities promoting healthy and more plant-based diets with low carbon footprint are expected to drive a substantial reduction of GHG emissions from the food sector. The development of standardized methodologies for assessing the impact on GHG emissions, biodiversity, water resources, human health, market value and job creation will strengthen the ability to assess whether, how and why plant-based food production and its impacts are changing and contributing to the strategic goals. Furthermore, research on existing public and private policies governing the production and consumption of food will form the basis for identifying potentials for introducing novel and innovative policy and governance arrangements that can function as drivers for accelerating the transition to more plant-based and sustainable food production and consumption.

BEST ESTIMATE OF SPECIFIC IMPACT ON THE STRATEGIC GOALS AND SOCIETY

In order to support the transition towards a food system where most of our food is sourced from plants, the timing and allocation of resources for all key activities need to be organized in a way that maximizes synergies and minimizes trade-offs. By providing incentives for consumers to change their behavior, we expect to see an increasing demand for healthy and sustainable plant-based food, and by providing incentives for farmers we should ensure that this increasing demand is met with a corresponding increasing production of food crops and plant-based food products manufactured with unprocessed and/or gently processed raw materials sourced from Danish farmers.

By 2030 it is expected that 50% of the population eat a primarily plant-based diet and that food waste has been reduced by 50%. Coupled with a rapidly expanding global market for plant-based food it expected that the area of food crops will increase from 300,000 to 600,000 ha, including between 100,000 and 150,000 ha pulses. If we optimize the efficiency of food crop production and use these pulses for the manufacturing of gently processed, nutritious and delicious 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 tons of 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 (Waite et al., 2019) based on the study by Poore and Nemecek (2018), this would reduce the global area required for producing feed with between 0.8 and 4.7 m hectares and reduce global greenhouse gas emissions with 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 (Henriksen, 2021). With less European and global land required for producing feed it will be possible to further reduce global GHG emissions by restoring organic soils and start planting trees on available agricultural land, with a total reduction corresponding to at least 50% of the GHG emissions from Danish agriculture. Besides contributing to reducing the climate impact of the global food system, the lower area required for feed will also contribute significantly to improving water resources and biodiversity. By applying new and improved traditional breeding technologies, optimizing management practices, improving farming systems, reducing waste, upcycling side streams and applying plant biologicals, AI and robotics, we will be able to compensate for a 50% reduction in pesticide use, reduce ammonia emissions, and increase the efficiency of food crop production with 10% by 2030. This optimization of crop production efficiency will contribute with a relative share of the reduction of global GHG emissions with between 0.5 and 1.1 Mt CO_2-eq.

By 2050 it is expected that 100% of the population eat a primarily plant-based diet and that food waste has been reduced to a minimum. Based on a further increase in the global demand for plant-based food it is expected that the area of food crops will increase by an additional 300,000 ha. Healthy, delicious and gently processed plant-based food products made from protein crops, specialty crops and other high value crops cultivated by Danish farmers are being supplied for the domestic market and exported to the European and global market, thereby contributing significantly to substitute the consumption of meat with plant-based food. With less European and global land required for producing feed, all organic soils have been restored and trees have been planted on available cropland, sequestering carbon and making more space for nature, and thereby contributing to turning 30% of land in Europe into protected areas. Together with additional efficiency measures, this will result in further reduction of GHG emissions and ensure the achievement of climate neutrality by 2050. Replacing chemical fertilizers and pesticides with biofertilizers, biological control and plant biologicals, will improve water quality, reverse the decline of pollinators and maintain long-term biodiversity. 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 b DKK per year (Jensen, 2021).

BUSINESS POTENTIAL AND ADDED VALUE BOTH IN DENMARK AND INTERNATIONALLY

There is a large business potential within Denmark as the consumer dietary change offers new business and sales for the sector nationally. An increased home-market of plant-based food production can enable export of agricultural systems and food products. Plant-based sector sales grew with 29% in sales and 46% in volume between 2018 and 2020. Denmark has a favorable image as a green nation and a trusted, high-quality food producer.

Plant-based foods have the potential to meet both climate and dietary needs of the future. Innovative private and public policies and governance arrangements for transitioning food production and consumption to being significantly more plant-based have the potential to make Denmark a first mover in terms of industrial and agricultural innovation. This would create opportunities for new business models and export of innovative and sustainable food products. There is also a potential for Denmark becoming a service exporter in terms of providing expertise in relation to private and public management systems and regulatory frameworks and Denmark can potentially become a leading innovative force in EU food and agricultural policy making. The global market for plant-based food is projected to grow at a CAGR of 11.9% reaching a value of 74.2 b USD by 2027 (Meticulous Research, 2020). Based on these projections and a recent analysis of job creation potential within the plant-based food sector in the US (Plant Based Foods Association, 2021), it is expected that 900,000 jobs will be established within the global plant-based food sector by 2027. With policies in place to support the transition towards more plant-based food production and consumption, it is expected that Denmark will be able to get a share of between 1% and 3% of the global market for plant-based food by 2030, corresponding to a market value of between 4.5 and 13.5 b DKK, and resulting in the creation of between 9,000 and 27,000 new jobs.

The global market for plant biologicals (biocontrol, biofertilizers and biostimulants) is rising. There is a significant business potential for Denmark to increase its share of the market. If the Danish R&D hub is consolidated, and the legal framework is in place, Denmark has the potential to be among the world-leading strongholds for biological products for agriculture. Production of plant-based ingredients is attractive to consumers and with high techno-functionality based on novel gentle processes and fermentation, it is expected to have a huge economic impact on Denmark's economy, because of a large worldwide demand. In this context, ingredients and plant-based food products made from Nordic crops are of special interest, as they are perceived as healthy and sustainable. Furthermore, processing equipment, microbial cultures, analytical equipment and robotics will be developed and have a large export potential to further strengthen the Danish exports and economy. Chr. Hansen (CH) expects that the market of fermented plant-based foods will contribute positively to the revenue of CH in the order of > 100 m DKK over the coming 5-year period. FOSS conservatively estimates a potential annual revenue of >50 m DKK by 2025 from instrument sales and digital services to the plant-based alternative industry. KMC expects that protein-based ingredients will increase the turnover for specialized ingredients by 10% over the next decade.

A strengthening of the plant-based food industry is further expected to improve brand recognition, return on investment for the Danish food industry, and support growth of the start-up and SME segment within the plant-based food solutions and associated technologies.

Inflection points and milestones

TECHNOLOGICAL READINESS LEVEL AND MILESTONES

Plant-based food production and its subareas lie between TRL 1 to 3 at present, with two frontrunner areas that have reached a higher level already. Most areas have the capability to have surpassed TRL 3-4 before 2025. With significant public and private investment in research and innovation, it is likely that TRL 9 can be achieved in 2030 in most areas. In general, it should be noted that 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 tech is further developed. Therefore, solutions are to be based on the current models with the limitations they may have and at the same time we need to develop hybrid LCAs with multiple sustainability criteria.

Until 2025

- Pilot studies with management of crops, cropping systems and farming systems completed. Climate footprint reduced by 20%
- Traceability and documentation systems developed and tested (TRL3)
- Test platforms regulation and guidance documents for plant biologicals, screening of relevant existing plant species for cropping applicability and beneficial nutritional, functional and sensory characteristics completed
- Air-based and land-based robots performing autonomous execution (under human supervision) of preplanned agricultural operations such as mechanical weeding implemented by multiple manufacturers and in use at multiple sites
- Established technologies for extracting food grade ingredients from waste materials
- Proof of concept of gentle extraction of proteins from a variety of plants and side streams including sustainable approaches and equipment for separation, purification and concentration of plant protein
- Fermentation and/or enzymatic approaches improve functionality, structure, taste and nutritional value
- Method developed for assessment of climate impact of different dietary patterns and related farming systems
- Method developed for assessing carbon opportunity cost and gains as part of GHG accounting
- Developed of adjusted LCA methodology based on attributional LCA for LCA of food products in life cycle perspective.

Until 2030

- Optimization and scaling of different types of food crop production systems completed. Climate footprint reduced by 50% (including novel crops, new breeding technologies and facilities, current and underutilized crops)
- Traceability system starts implementation in the value chain and undergoes continuous development and adjustments (TRL5)
- Knowledge regarding pathways for nutritional and anti-nutritional compounds established
- Verification of usability (food industry and consumer)
- Full-scale commercial production and cost competitive of ingredients from waste materials
- Established technologies for handling and utilizing all parts of crops
- Established IT technology for smart logistics.

Until 2050

- Diversification of food crops and development of climate neutral farming systems completed. Climate footprint reduced by 100%.
- The traceability system is acknowledged as the preferred system worldwide
- 10 % animal-based food replaced by products produced with ingredients upcycled from feed materials and side streams.

SOCIETAL READINESS LEVEL AND MILESTONES

In 2021 plant-based food production and most subareas lie between SRL 2 to 3 with plant biologicals as a frontrunner area at SRL 6. Most areas have capability to have surpassed SRL 4-5 in 2025, and in 2030 the subareas will be between SRL 7-9. All will be at SRL 9 before 2050.

› Track C Plant-based food production

The plant-based food sector is growing with at least 30% growth rates and is expected to triple by 2025. This is an important driver in the societal acceptance and readiness. The demand and consumer readiness for plant-based foods are rising, but the production level, selection and consumption of plant-based food are still limited (SRL2)

Milestones mentioned below will be the main drivers of the innovation and transition:

Until 2025:

- 50% of the population has a vegetarian lunch and dinner at least twice a week and 24% are eating a predominantly plant-based diet
- Long term strategies for transition in public kitchens in place
- Stakeholders identify key barriers to system-wide transition and test out associated solution spans at small scale (SRL3) and then implement a test for viability of coordinated transition across all links in value chain (SRL4) and finally validate the need for further regulatory and other adjustments that stand in the way of accelerated change towards sustainability (SRL5)
- Identify innovative demand-side policy measures in the EU and national agri-food policy policies and evaluate their potential for upscaling as well as functioning and effectiveness of private regulatory schemes in the food sector
- Evaluate the potential for using private and hybrid regulatory schemes for creating demand for plant-based food
- Outline pathways for transition of public, private and hybrid policy and governance arrangements to promote sustainable production and consumption of plant-based food.

Until 2030

- By 2030, the assortment of plant-based foods and beverages has exceeded meat and dairy products in the supermarkets, with 50% of the average consumers eating a primarily plant-based diet by e.g., increasing their consumption of legumes from 5 g/day to 100 g/day (SRL4).
- Alternative food products and food products from waste streams accepted by mainstream consumers.

Until 2050

- By 2050, 100% of the average consumers are eating a primarily plant-based diet by e.g., consuming 100 g legumes per day and having reduced their meat intake to 50 g/day (SRL9).

Risk management and alternatives

The major alternative to the proposed transition towards more plant-based food production and consumption is that Denmark remains primarily a large-scale animal-based agricultural exporter, with associated risks to the ability to fulfill long-term national climate and biodiversity goals.

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.

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 living beings, the private and public policies to transform agricultural production to being more plant-based should be evaluated regarding:

- Sustainability goals and ensuring that it does not result in carbon leakage
- How beneficial microorganisms behave under various environmental conditions and the effectiveness of strategies for biosafety, biosecurity, and biocontainment
- Inefficient logistics due to the qualitative and quantitative (volume) characteristics of the raw materials and ingredients (for example, frequent and unutilized transportation)
- Resistance from inhabitants from nearby areas due to noise and smell and other nuisances.

Increased consumption of plant-based food, including legumes, and a concomitant lower intake of animal protein need to be carefully investigated for:

- Content of harmful components or allergenic substances. Risk analysis and assessment is critical for registration of new products, official approval and consumers acceptance
- If it meets nutrient requirements in the body during different stages of life and if diets are nutritiously balanced. Mitigation: Nutrition education in schools with a focus on the variation of the diet, taste experience of plant-based foods. Clarifying popular beliefs and alliances with social media influencers
- Risk of consumers' incorrect food handling and food safety behavior when attempting to reduce food waste.
- Mitigation: Investment in improved cooking skills, education about food safety

For AI and robotics, the value proposition and legislative incentives (carbon taxation/nature protection) is currently not sufficiently strong for farmer uptake of technology.

Relation to other tracks

Plant-based food production and consumption inflict on cultural, behavioral, structural and institutional barriers that will affect the options for producing food crops for human consumption at the individual farm level.

The track enables impact assessment as part of the innovation, operation and reflexive governance of plant-based food production and consumption and its interactions with other food and agricultural systems. It also includes assessment of different farming systems and crop production methods on GHG-emissions, water resources, biodiversity, human health, market value and job creation.

It has overlaps with other tracks in terms of; Regulation and incentives, including public and market incentives as well as consumer based; Co-development processes, living labs and demonstration farms; Aligning the green transition with rural development and local participation processes; Co-production of renewable energy with agricultural production; Financing the green transition, circular economy, Arable cropping systems; Forage crop production; Perennial cropping systems; Circular biomass and nutrient flows at farm and landscape scales – all of these areas are relevant to plant-based food production, as well as all other tracks. Data protocols and data-sharing systems are enabling transparency in the food systems and across spatial and organizational scales, and they are a prerequisite for effective use of AI and robotics. This is relevant to management and precision livestock farming, sustainable processing of raw materials, creation of digital twins of plants and for optimization, and robotic manipulation relevant for high-value crops.

Plant-based food production will inflict on the options for the individual farmer to develop and finance a business focusing on producing food crops for human consumption, taking both animal and plant-based food production into account as well as land use.

There are close links to the consumer and demand-related topics in the crosscutting topic that includes consumer drivers as well as Animal-based food production and Land use & management.

List of concrete goals and related key activities

BARRIERS AND POTENTIALS
What are the concrete goals?

Until 2025

- Identify and co-create new actionable knowledge on select transition pathways and value chains where Denmark has potential as a future stronghold for plant-based food production.
- Build transdisciplinary research capacities that span the entire food system and leverage this research for smart planning and management of food system transition.
- Bring together key actors from across all links in the value chain to build mutual trust, shared knowledge on how to overcome barriers, and shared understandings of smart policy mixes.

Until 2030

- 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.
- Consolidate and spur growing domestic demand for plant-based proteins, as well as Danish companies' larger-than-average share of the growing international market.
- Further the contribution to national climate and biodiversity targets by verifying direct emission reductions and sequestration from changing land use (e.g., forests).

Until 2050

- Incentivize, 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.
- 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.
- 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 select and crosscutting 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.

COLLABORATION AND VALUE CHAINS
What are the concrete goals?

Until 2025
- Describe, screen, and develop what we already know
- Establish a strong and well-connected plant-based value chain by learning from the animal-based value chain and using living labs as a method for cluster formation, user involvement and local community engagement

Until 2030
- Full traceability and documentation of sustainability for logistics and door-to-door transportation is implemented
- The digital infrastructure will form the basis for new business opportunities and circular business models is a prerequisite in the plant-based value chain
- The technological gaps and incoherent value chain are established and implemented

Until 2050
- Innovation and new development of sustainable and circular workflows are developed, tested and implemented
- Related key measures and activities in the very near future
- Establish strong cooperative communities
- Establish strong support and advisory systems for initiating or transitioning into sustainable production and circular thinking among actors in the plant-based value chain
- Provide sustainable pricing, contractual basis and supplier agreement in cooperative communities
- Targeted funding and investment in the value chain

NEW AND IMPROVED TRADITIONAL BREEDING AND PROPAGATION TECHNOLOGIES
What are the concrete goals?

Until 2025
- Identify nutritional traits and develop method for efficient early prediction based on genomic and transcriptomic data, allowing screen of large populations
- Establish infrastructure for efficient NBT-based technology and phenotyping facilities for screening of the developed phenotypes, including analysis of big data
- Knowledge how to obtain more yield and robust plants, by increasing biomass and resistance to biotic and abiotic stress

Until 2030
- Phenotyping, efficient NBT-based technology and utilizing omics' information to increase adaptability, yield and genetic gain implemented in breeding programs in all relevant crops
- Robust crops with higher yield developed and multigene biomarkers identified for abiotic stress, together with known mechanism for disease resistance implemented in breeding
- Implementation of high-quality traits, removing anti-nutritional factors and optimized functional qualities in food and food-based products
- **Until 2050**
- Breeding programs that combine omics technologies, NBT and phenotyping for selection in an efficient way in breeding programs
- Mature markets established for crops imparted with human nutritional and functional assets
- Competitive commercial varieties with drastically improved yield, disease resistance, combined with stress resilient varieties, based on multi-gene interactions

Related key measures and activities in the very near future
- Improvements of traits for high quality, optimal nutrient profile and anti-nutritional factors in harvestable parts of crops
- Increased harvestable grain, tuber or root yield with conserved or improved nutritional and functional value to give the same productivity in less land
- Combined use of genomics and omics technologies and new breeding technologies will be tools used for all crops when developing and selecting high yield and robust plants
- Robust plants will have better resilience toward expected climate changes with more extreme weather events and diseases, ensuring yield
- Genomics-based improvement of traits for protein, carbohydrate and oil constituents, nutritional value, process stability and sensory functionality for most important crops.

NEW FOOD CROPS AND FARMING SYSTEMS
What are the concrete goals?

Until 2025
- Screening of selected crops potentially suitable for human consumption to determine their cropping applicability and profitability, as well as their nutritional, functional and sensory characteristics
- Pilot studies featuring soil, crop, nutrient, water, light and CO_2 management as well as methods for enhanced circularity for controlled environment agriculture systems completed
- Pilot studies with stockless food crop production systems and mixed food crop and low-density livestock production systems with perennial crops, intercropping and agroforestry have been completed

Until 2030
- Cultivation of existing crops suitable for human consumption and demanded by consumers has been optimized through multi-stakeholder collaboration
- Management practices for CEA stockless food crop production systems and mixed food crop and low-density livestock production systems have been optimized and scaled for use under different soil and climatic conditions
- With a substantial number of farmers earning a part or all their income from producing food crops it will be possible to reduce the area required for feed production restore all organic soils

Until 2050
- Cultivation of all relevant crops featuring a diverse range of genotypes having nutritional, functional and sensory characteristics suitable for human consumption has been optimized and implemented in practice
- All food sourced from CEA systems, stockless food crop production systems, and mixed food crop and low-density livestock production systems is climate neutral or even carbon negative

Related key measures and activities in the very near future
- Development of management practices targeted towards producing food crops for human consumption ensuring improved fertilizer management, nutrient use efficiency and soil and plant health
- Mixed intercropping, strip intercropping and relay intercropping strategies with legumes and cover crops should be applied to increase soil cover, reduce nutrient loss and increase soil carbon sequestration
- Diversification of cultivation methods for controlled environmental agriculture, including vertical farming and traditional greenhouses
- Reducing food waste during crop production, harvest and storage, handling of unavoidable food waste to recover nutrients, upcycling and recycling of side streams from food production
- Optimization and scaling of stockless food crop production systems, mixed food crop and low-density livestock production systems and controlled environment agriculture systems

PLANT BIOLOGICALS
What are the concrete goals?

Until 2025
- A test platform for biologicals will be established that combine laboratory methods as well as greenhouse and field-testing facilities
- Clear, legal testing requirements and guidance documents for biologicals are drafted and a Danish conformity assessment body has started to test biologicals
- Studies have been carried out on social and cultural aspects, consumer acceptance, ethics and policy impacts of using biologicals for plant-based food production

Until 2030
- Several new biological products are introduced to the market or in the process of being approved, and farmers, advisors and retailers have been educated on their use
- Both large, medium-sized and small companies are able to achieve market approval for new biological products within a reasonable time and financial frame
- There has been an open dialogue with consumers about the benefits and potential risks of using biologicals and there is a common understanding of biologicals in the public

Until 2050
- A host of new biological products are on the market and the use of these products are widespread in plant-based food production, reducing the use of agrochemicals
- The plant biologicals hub in Denmark will be internationally recognized as a driving force for research and development of biologicals

- The Danish approval system for plant biologicals is among the most efficient internationally and Denmark will contribute to paving the way for an increased use of biologicals globall.

Related key measures and activities in the very near future

- Establishing a test platform for biologicals in collaboration between researchers, industry and authorities that can test and document the mode of action, efficacy and risks of biologicals
- Giving input to and working with Danish authorities to draft legislation on documentation requirements for biological products
- Establishing an information organ to ensure that legislators have access to relevant information and the latest research on the area
- Initiating studies on social and cultural aspects, consumer acceptance, ethics and policy impacts
- Drafting and implementing a solid communication plan to alleviate public concerns and misunderstandings about the nature and use of biological products

AI AND ROBOTICS

What are the concrete goals?

Until 2025

- Drones autonomously gathering relevant information (automatic take-off, mission planning, and landing) at a pre-planned location and time but without human supervision
- Automatic processing of information gathered by drones and other sensors to extract relevant KPIs and to propose operations to be performed by agricultural robots
- Fleet of agricultural robots performing relevant operations on high-value crops under human supervision

Until 2030

- Fully autonomous drones gathering relevant information (automatic take-off, mission planning, and landing) on demand in several locations and without human supervision
- Automatic processing of information gathered by drones and other sensors to extract relevant KPIs and to generate plans for operations to be performed by agricultural robots
- Fleet of agricultural robots performing automatically planned operations on high-value crops without human supervision

Until 2050

- Fully autonomous drones and agricultural robots managing high-value crops without human supervision, including automatic processing of information and planning of operations

Related key measures and activities in the very near future

- Autonomous systems: Techniques for safe and reliable operation of autonomous, self-monitoring mobile robots (land-based and air-based) operating in the presence of humans
- Land-based robots: Techniques for controlling fleets of land-based robots to efficiently perform high-precision operations, such as mechanical weeding, on smaller areas of high-value crops and under human supervision
- Drones: Autonomous BVLOS operations, including automated take-off, landing, and recharging, supporting large drones capable of longer-duration flight and performing precision spraying
- Perception and AI-based analysis: Robust perception techniques that can collect data in varying environmental conditions to maintain digital twins (digital models) of crops, enabling automatic crop analysis and simulation-based optimization
- End-user programming of robots and collaborative robots: Principles and techniques for end-users to control the actions of robots, both off-line (programming) and on-line (in the field)

UPCYCLING AND RECYCLING

What are the concrete goals?

Until 2025

- Robust proof of concept and proof of scale on extracting food grade proteins from perennial leaves; and implementation of food grade protein production in grass biorefinery factories
- Proof of concept, proof of scale and business models on producing fungi, insects and micro-algae on nutritious side streams from food production by establishing 3-5 pilot supply chains and models of logistic networks
- Proof of concept and proof of scale on upgrading side streams into nutritious products, including establishing pilot supply chains and models of logistic networks

Until 2030

- Developed several novel innovative food ingredients and products from agro-industrial side streams and has increased export of these products and technologies

- Replaced animal-based food by 10% through novel innovative products from upcycling feed to food and from utilization of agro-industrial side streams
- A number of circular networks and synergies have been established together with associated logistic networks based on IT platforms, and have reduced import of soy by 20%.

Until 2050

- Replaced animal-based food by 50 %
- Increased export of plant-based ingredients and products with 50% more value than the value of animal-based food export in 2021
- Efficient and fully circular food systems where most parts of the agricultural crops are used for food and health ingredients, and with no waste and bac- looping nutrients

Related key measures and activities in the very near future

- Established technologies for extracting food grade proteins from leaves of grass, clover and Lucerne and pilot production
- Established technologies for extracting food grade ingredients from agro-industrial side streams
- Established novel fermentation platforms for solid state fermentation for upgrading agro-industrial side streams and pilot production
- Established commercial scale insect production and pilot scale microalgae production
- Developed a number of novel innovative nutritious (EU approved) food ingredients and products

SUSTAINABLE PROCESSING OF RAW MATERIALS

What are the concrete goals?

Until 2025

- Competitive industrial production of high-quality plant ingredients in Denmark
- Mild extraction and fractionation processes for plant raw materials developed at pilot scale
- Potential cultures and enzymes for gentle processing are identified

Until 2030

- Mild extraction and fractionation processes for plant-based implemented industrially
- Cultures and enzymes available for improving taste, nutritional value and functionality
- Multi-level analytics and process analytical technologies for designing, analyzing and controlling processes emerging to ensure quality, safety and functionality

Until 2050

- Novel robust processes, based on enzymes or novel technologies e.g., robotics, to gently recover valuable compounds from plants or side streams
- A diversity of Nordic plant-based ingredients of high-quality protein ingredients from Nordic crops and Denmark in a leading position in international trade
- Equipment solutions, robotics, cultures and enzymes produced in Denmark are exported
- Related key measures and activities in the very near future
- Identifying and characteriing new crops or side streams from molecular to a structural level by integrating knowledge from agricultural production and plant structure
- Improving production processes and product properties, e.g., techno-functionality by multi-level analytics and process analytical technologies
- Developing multiple fractionation processes, based on sustainable technologies, such as membrane filtration, separation, purification and concentration of proteins with techno-functionality and/or improve nutritional value
- Developing solutions for removal of off flavors and antinutritional factors, and improving taste and texture by fermentation
- Developing enzymatic-based approaches to improving techno-functionality, taste and nutritional value of ingredients

PLANT-BASED FOOD PRODUCTS

What are the concrete goals?

Until 2025

- Increase consumer acceptance and consumption of affordable plant-based foods
- Deliver a suite of new plant-based food products that are nutritionally and sustainable validated for both the domestic and international markets
- Reduce food waste along the food system, valorize side streams to deliver an increasingly sustainable plant food system.

Until 2030

- Deliver a suite of smart solutions and technologies that reduce plant-based food waste along the food system, that are commercialized globally
- Deliver new fermentation solutions specifically developed for plant-based foods, for dairy and meat analogs
- Solve the challenges of plant-based food in relation to functionality, safety and nutrition

Until 2050

- The Danish food industry delivers new plant-based food formulations, solutions and technologies that ensure Denmark as the leader in the plant-based food system, driving the global shift to diets with a low carbon footprint
- Energy and water consumption in food processing has decreased by 50%
- Denmark is internationally recognized as the leading expert in fermented plant-based food products

Related key measures and activities in the very near future

- Consumption of plant-based food increased 100% in Europe
- Export of plant-based foods increases – market share of Danish companies producing plant-based foods increased 500%
- Reduce food waste along the plant-based food system by 25%, thereby securing a circular economy
- Acceptability parameters of plant-based food increased by 200%
- Denmark has an export in starter cultures and fermented plant products equivalent to the position within dairy products in 2021

CONSUMERS AND DIETARY CHANGE
What are the concrete goals?

Until 2025

- 50% of the population has a vegetarian lunch and dinner at least twice a week
- Plant-based food sector growing with at least 30% growth rates, has tripled since 2019
- Long term strategies for transition in public kitchens in place

Until 2030

- 50% of the population eat a predominantly healthy and sustainable plant-based diet
- Consumption of legumes and pseudo-cereals has increased at least ten-fold (from 1 kg/person/y).
- The market for plant-based food alternatives has grown with 30-50% annually in terms of revenue and sales volume, and has diversified

Until 2050

- 100% of the population eat a predominantly healthy and sustainable plant-based diet
- Food waste is reduced to a minimal amount
- Public meals are delicious, predominantly (depending on nutrition demand of target group) or fully plant-based, environmentally sustainable and ethical
- Related key measures and activities in the very near future
- Research on citizen-consumer behavior change, transition pathways and societal tipping points through long-term, large-scale observations and interventions, including nudging.
- Consumer-targeted tasty, healthy and sustainable food and meal development applying advanced consumer research on preferences to model-optimized and individualized diets
- Developing and capacitating professional kitchens and staff towards offering plant-rich and predominantly plant-based meals in line with the Danish guidelines and planetary health.
- Development, testing and evaluation of a mandatory food labelling improving comparative and condensed consumer information at the point of sale on both health and sustainability
- Establishment of cross-value chain partnerships and targeted social marketing campaigns for increasing the market for diverse Danish food crops for human consumption (e.g., legumes)

IMPACT ASSESSMENT AND SUCCESS CRITERIA
What are the concrete goals?

Until 2025

- Methodology for farm-level GHG emissions, and carbon opportunity gains and costs of diets and farming systems and for impact assessment on biodiversity goals developed
- Partial equilibrium models and trade models including climate policy scenarios and agro-sector performances from across the world tested
- Methods for assessing impact on employment and competence needs in the Danish food and agricultural firms from plant-based food production and consumption developed

Until 2030

- Methodology for expanded Product Environmental Footprint (PEF) with carbon opportunity gains and costs implemented for food products and applied in certification schemes
- Methodology for determining water footprint in different stages of the food value chain developed and implemented in relevant certification schemes for food products
- Expansion to include leakage of environmental impacts and direct and indirect land use effects will be ready for use in environmental policy analysis

Until 2050

- Climate neutral Danish agricultural production at national territorial level has been reached and documented by the farm and national inventory tool
- Goals for biodiversity have been reached and documented by the multicriteria sustainability impact tool
- Substantial part of the Danish population is predominantly eating plant-based food and the changes have increased the expected lifetime of the Danish population

Related key measures and activities in the very near future

- Methodology for determining farm-level GHG emissions and for assessing carbon opportunity gains and costs of different dietary patterns and farming systems developed and applied
- Biological biodiversity, agro-biodiversity and landscape diversity goals identified and methods for impact assessment and possible measures to reach the goal developed
- Methods for analyses of drivers and barriers for changes in dietary practices towards plant-based food consumption developed and included in national dietary surveys
- State-the-art sector partial equilibrium models and trade models including climate policy scenarios and agro-sector performances from across the world developed and tested
- Impact on employment and competence needs in Danish food and agricultural firms from plant-based food production and consumption assessed and applied in education strategies

DRIVERS AND MEASURES
What are the concrete goals?

Until 2025

- The first wave of research findings on private governance and innovative niche public policies will be published
- Market actors would be initiating and experimenting with new and innovative private regulatory frameworks supported by some public policy initiatives
- Scholars would be feeding evidence and expertise in to such activities

Until 2030

- Scholars would be engaging with policy and market actors in relation to evaluating the policy and governance experiments and initiatives
- Retailer-led initiatives and national public policy measures directed at the demand-side will feed into discussions on how to shape the EU Common Agricultural Policy (CAP) post-2030

Until 2050

- Retailer-led food regimes would have matured and transformed the food system. Most of the food would be sourced from plants
- Retailer engagement as well as government experiments with the demand-side policy measures would have forced the CAP to transform to a sustainable food policy
- During the transition process, scholars would have supported the effort by producing evidence and scholarly input
- Related key measures and activities in the very near future
- 2022: Research projects are selected and start-up activities are initiated. Initial engagement with partners takes place
- 2025: Research activities are generating the first results and the findings are beginning to be disseminated through scientific publications, policy briefs and stakeholder workshops.
- 2030: Research has expanded from small/medium-N studies to large-N studies. Research findings used in experiments with novel and innovative public policy and private governance
- 2050: Activities related to 'export' of Danish and European experiments will have matured

BUSINESS PLANS AND FINANCING
What are the concrete goals?

Until 2025

- First steps in plant-based scenario co-financed by mainly public funding sources (research grants, private foundations, basic research funds) due to low TRL/SRL levels
- Consumer attitudes surveyed and influenced (Denmark and internationally) and primary producers' change barriers addressed – from low-value feed to high-value consumer-oriented food
- Product and process innovation schemes in SME equipment industry in place

Until 2030

- Crowd-funding based financial instruments and sector-based cooperative co-financing of innovation further enhanced to support transition to plant-based agriculture and food
- Start-up eco-system with focus on scalability established
- Industry investments from large industry players based on high TRL/SRL and transformational strategies to 'go green'

Until 2050

- Investment attractiveness from and citizen-based financial instruments and financial equity instruments have increased in plant-based agriculture and food due to high profitability based on knowledge-based high-value plant-based ingredients and internationally unique and well-branded end-user products
- Sector-financed innovation as well as co-funding for new research-based knowledge are supported by high profitability
- Processing equipment sector (AI, robotics, environmental efficiency) established and supported by targeted innovation schemes and focused world-class education

Related key measures and activities in the very near future

- Enable access for suppliers, producers and retailers to information sharing portal (block chain) to share information with the end user (transparency and traceability)
- Implement best practice and continue research regarding supply chains with minimal loss and waste
- Stimulate experimentation with new business models and enhance market access for entrepreneurs with new concepts and technologies
- Knowledge sharing, innovation and fast implementation in existing industry

TRACK D **BIOTECHNOLOGY-BASED FOOD PRODUCTION AND ALTERNATIVE PROTEINS SOURCES**

Vision

The vision of track D is to reduce the harmful impacts of food and feed production on climate, environment, and biodiversity through biotechnological solutions. Further, we envision lowering the land use required for feeding the growing global human population through optimized resource use and the biotechnological production of novel foods.

This will be enabled via i) biorefining for feed and food, ii) cellular agriculture including stem cell meat, cellular milk, microalgae, precision fermentation, iii) microbiome engineering in agriculture, aquaculture, and bioprocesses, iv) microbial and enzymatic upgrade and value-added products from side streams, and v) alternative proteins. These five areas represent vast and growing value pools where Danish industry has significant strongholds. Thus, there is a great potential for accelerating sustainable solutions to meet the global challenge of increasing the sustainable production of safe, tasty, and healthy food.

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. One of the major global challenges is to innovate solutions to make traditional production of food with high-value protein more sustainable and to develop novel alternatives to traditional animal-based foods to meet the needs of the growing population. An integral part of this challenge is the simultaneous reduction of the adverse impacts from food production on climate, environment, biodiversity, and land use.

The focus thus far, has been mainly on transforming biomass to energy and bulk lower-value chemical commodities to facilitate the transition to the bioeconomy. There is a tremendous untapped potential in the transformation of non-edible residues from biomass or its side stream into higher value foods and feeds. Deploying state of the art biotechnology tools including cellular and enzyme biocatalysts; using biologics at all steps of food and feed production as well as of smart biorefinery concepts is instrumental to harness the potential of biomass in higher value food and feed products.

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. Also, biodiversity is challenged by the widespread use of agro-chemicals (antibiotics, pesticides, fungicides) and replacing these with sustainable bio-based solutions is a key goal.

Since milk and meat production is one of the more significant contributors to GHG emissions we need to find new sustainable ways to produce our traditional high-quality foods and ingredients, but also to utilise our existing resources more efficiently, include alternative sustainable protein sources and find new ways of producing the high-value animal proteins. Thus, there is no single solution to combat the challenge. To enable this transition, it is necessary to develop a plethora of complementary sustainable, bio-based alternatives and engage in a broad range of innovations in a series of workstreams elaborated below.

The use of agrochemicals in agriculture and aquaculture contributes to soil, water and air pollution, biodiversity loss and can harm non-target plants, insects, birds, mammals and amphibians. The EU Farm to Fork strategy sets the target to reduce by 50% the overall use and risk of chemical pesticides and reduce use by 50% of more hazardous pesticides by 2030. Chemical agents secure high global crop yields but as they are a risk to our environment and biodiversity, an increasing number of agents will be banned by EU. Organic farming practice has gained more interest by consumers and farmers but represents still only a smaller part of the food production. Strategies to replace chemical pesticides with biological alternatives are therefore needed. There is a significant challenge in replacing synthetic chemical plant protection agents with new biologicals, including innovative low-risk biologicals such as new species/strains of microorganisms, pheromones and/or microbiome solutions. The challenge is complex as the transition to biologicals inhere the risk of large drops in crop yields that in turn could increase CO_2-demanding inputs like fuel, fertilizers and the required land use to meet global food and feed demand and thus contribute to accelerated deforestation and climate change. There is thus a potential large climate penalty for the transition to biological agents that must be reduced or eliminated. The timeline for new biologicals to progress through the discovery, development and regulatory approval phases is often 6-8 years, so action is urgently needed to develop novel biologicals. The workstream on microbiome engineering addresses the challenge.

› Track D Biotechnology-based food production and alternative proteins sources

Greenhouse gasses are consumed and produced by various soil, water and animal microbiomes. Therefore, microbiome engineering to reduce emissions of such gases can lead to great impact. Precision-editing of the animal microbiomes for example, is an important viable route to improved animal health, reduced animal mortalities and enhanced feed conversion rates, all contributing 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.

Key activities and workstreams

Each workstream contributes to different Innomission targets and are characterized 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

TABLE 9 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** Behavior (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, FOOD AND NON-FOOD USE
To further develop the Danish biobased economy, we must aim to utilize biomass for as much added value products as possible, and for the most appropriate application. This principle of cascading use of biomass cuts across numerous domains, as biomass can be used for food and feed, chemicals, materials, health and medicinal purposes and renewable energy. Several components in biomass can be isolated using biorefining technologies, such as pre-treatment, fractionation and separation techniques, and fractions can be upgraded to high-value products through advanced processing. These components are assigned their own possible applications depending on their market value. In this way, cascading and biorefinery allow us to increase the economic value of biomass. The Danish food and agriculture sector has a long tradition of developing waste streams into side streams of novel high-value products, and current research & innovation activities are accelerating this transition to a bioeconomy where biomass is used to its full potential. Biorefining further opens a vast potential for a transition in land use from annual crops to perennial crops as described in the above track on land use as the market value of perennial crops may be at par with or surpass the market value of annual crops. Novel green biorefineries and particularly grass biorefineries have progressed fast during the past few years as two demonstration plants for green leaf proteins and two full scale commercial grass biorefinery plant are in operation in 2021 for production of protein for feed of monogastric animals. Whilst green biorefineries (clover, grasses and alfalfa) have reached an important value inflection point with the establishment of a full commercial-scale plant for feed production, efforts are needed to develop food ingredients and improve the efficiency of processing steps for utilization of the side streams for high-value products, as potentially valuable fractions are currently destined for biogas production. The fibre fraction for instance, exhibits properties useful for food and non-food products that must be researched and developed. This workstream requires further research and needs to develop cost-effective ways to remove the green color, inhibit browning and improve sensoric quality as well as functional properties of green grass proteins for food and test applications in food matrices. Food products must be Novel Food compliant and nutrition, toxicity and allergenicity assessments should be integrated from TRL4-5 onwards.

This workstream takes the green biorefinery concept further to develop refineries for pulses with particular focus on peas, lupin and faba beans. Evaluation of feed value of dehulled faba beans and appropriate varieties is in progress. Research and development efforts will include valorization of side streams and evaluation of environmental and climate effects. As for green biorefineries, different process technologies have been tested to reach the quality needed for utilization in food. Preliminary tests of the quality parameters and functional properties of green protein concentrates have demonstrated promising traits but also a need for further research and technology development to reach a quality that is acceptable for commercial utilization.

Downstream fractions from biorefineries are often used for biogas, and the advanced Danish biogas infrastructure represents an important element in valorizing low value biorefinery side streams. However, as biogas is subsidized, the biogas sector tends to receive biomass fractions that potentially could have been processed and upgraded to higher-value products than biogas. In the emerging bioeconomy, it is critical to use biomass to its full potential, so efforts must be made to research and develop side stream valorization, deploy quantitative sustainability assessments (QSA) including life cycle assessment (LCA) and revise the regulatory incentives for biogas. In addition, the organic compounds remaining after gasification for biogas production represent potential value for biofertilizers, as substrate for e.g., mushroom production or for further bioenergy production including syngas, pyrolysis and hydro-thermal liquefaction (see also section on crosscutting issues below.)

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 has reached SRL9. We expect inflection point for the feed fraction to be achieved by 2023-25; for the grass-based food fraction by 2025-27, and pulses-based food fraction by 2027-29.

CELLULAR AGRICULTURE - STEM CELL MEAT, CELLULAR MILK & EGG, MICROALGAE, PRECISION FERMENTATION

"If sustainability is your long-term game, then fermentation is the future." (Kevin Brennan, Quorn's ex-CEO).

In many meals, meat, milk and eggs contribute with proteins and fat and apart from high protein digestibility and a well-balanced amino acid composition, animal-based products also supply important minerals, vitamins, functionalities and taste. However, traditional meat and milk production is challenged, because it draws heavily on land and water resources and contribute significantly to greenhouse gas emissions. Precision fermentation offers the opportunity to produce food ingredients in a sustainable and resource-efficient way by using renewable feedstock as carbon and nutrient source for fermentation and by using appropriate microbial strains. The optimized natural or recombinant expression of complex molecules, such as proteins, fats or other ingredients, allows mimicking or substituting culturally important food products like meat, milk and egg. Cellular production of meat, milk and egg are future ways to produce the same nutrients, with severely reduced impact on climate and the environment and freeing up land for other land use and ecosystem services. Cell-based fermentations (microalgae, yeast, filamentous fungi and bacteria) provide a tremendous opportunity to sustainably produce proteins and lipids in biosafe environments, controlling the composition and optimizing for nutritional and functional properties. Denmark is the base for large and strong biotech companies including manufacturers of enzymes and ingredients for the food industry as well as strong academic research environments within both biotech and food. This topic will bridge the gap between tissue engineering, biotech and food science to enter the fast-growing body of international research and start-up companies in the cultured meat area and cellular milk & egg, with an expected similar development regarding cultured milk, where only a number of early-stage international start-ups are emerging. Cultured cellular food production offers a future sustainable food solution with large perspectives and business potential. In order to take advantage of the Danish stronghold, interdisciplinary collaborations within and across academia and industry needs to be established. As an integral part of collaborations, it is critical to educate new talent for future developments.

The aim of the workstream is to establish sustainable cellular production of meat, milk and egg and reach parity with animal proteins with respect to taste, texture and price. The workstream thus comprises i) microorganism-based recombinant protein production using bacteria, yeast, algae or fungi and ii) animal-cell-based protein production.

Microorganism-based protein alternatives need to progress in five key areas to achieve parity on taste, texture and price, including:

a) Increasing metabolic efficiency through choosing the right platform strains, developing genetic engineering tools and adjusting the growth conditions to induce the microorganisms to higher yields of protein from fewer inputs in less time and with less production of off-flavours.
b) Adopting low-cost feedstocks to bring down the cost of microorganism-based protein production. This involves identifying feedstocks that are less expensive than the glycerol and glucose commonly used today. This may entail using side streams from other processes, which in turn not only lowers the price but adds additional elements of circularity and sustainability to microorganism-based protein production. The challenges herein include adopting low-cost feedstock overcoming inhibition of complex media and lack of understanding about relationship between strain and cultivation conditions.
c) Optimizing nutritional content, product functionality and posttranslational modifications.

d) Optimizing the harvest and protein extraction processes. Precision fermentation involves multiple steps from suspension to protein extract. Optimization and scaling of these processes significantly impact production costs and hence contribute to closing the gap to price parity. The challenges herein include sustainable and efficient purification; upscaling; circularity with efficient nutrient recovery; efficient and appropriate waste/by-products management and wastewater technology.
e) Clean-label functional additives contribute to sensory quality of microorganism-based protein solutions including taste and texture, and further research and development in clean-label functional additives and innovation with new ingredients is required.
f) Food safety, nutritional quality and health implications of purified ingredients vs. full original product are paramount to reaching product parity and consumer acceptance, and include regulatory approvals and potentially development of the regulatory landscape (GMO/novel food).

Animal-cell-based protein alternatives may be progressed to a level providing meat equivalent to fresh meat and with reduced or removed unhealthy saturated fat. Furthermore, cellular milk from cultivated bovine cells is an emerging technology to produce future milk components and ingredients. To develop animal-cell-based alternatives we need to progress along the same lines as the aforementioned microorganism-based solutions:

a) Increase metabolic efficiency
b) Reduce media cost; switching from pharmaceutical grade media ingredients to less expensive food grade ingredients and; recycling media, removing waste and adding nutrients
c) Differentiate muscle cells to grow fibers and fat, develop scaffolding solutions and improve sensory qualities
d) Upscale cultivation of bovine mammary cells in bioreactors to produce milk constituents

In particular, the workstream will progress as follows:

Cellular production of meat: i) Identify the optimal cell type/combination of cells for production of cultured meat, ii) Identify cost-efficient and consumer-acceptable ingredients for the culturing media, iii) identify suitable attachment surfaces for cell adhesion, proliferation and differentiation of muscle cells, iv) identify optimal bioreactor design, v) evaluate nutritional and sensory quality compared to conventional produced meat.

Cellular production of milk & egg: i) Identify the optimal cell type/combination of mammary cells with the strongest potential for establishment of robust cell cultures, ii) identify cost-efficient and consumer-acceptable ingredients for the culture medium, iii) optimize cell culture conditions and culturing systems, iv) evaluate secretion ability and identify components secreted, functional properties, v) Identify potential for up-scaling of milk production in bioreactors, vi) evaluate nutritional and sensory quality.

Microalgae for cultured meat and milk production:
i) Isolate strains that grow fast at high cell densities in bioreactors autotrophically or phototrophically, ii) develop molecular tools, ensure genetic stability, iii) select strains optimized for composition of proteins, lipids and carbohydrates, growth, yields, and nutritional quality, iv) bioreactor design for sustainable and safe production, v) combining phototrophic microalgae with cultured meat and cellular milk production.

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
The objective of this workstream is to reduce the climate impact of food and feed production by manipulating the microbial community of soil, animals, plants, algae and bioprocesses to mitigate climate change by improving growth, reducing disease in plants and animals and by transforming side streams to valuable products. As microbiome engineering is a technology with relevance for many areas (e.g., agriculture, aquaculture, and in bioprocesses), it holds a great potential to contribute significantly to the overall climate goals of reduced GHG emissions as well as to environmental goals of reduced N&P leakage and improved biodiversity.

Key areas covered include:

a) Microbial inoculants, biopesticides and biofertilizers in agriculture, with the main aim to improve biological crop protection by microbial biocontrol products that can replace chemical agents and contribute to eliminating the climate penalty related to phasing out of chemical pesticides. Biofertilizers will reduce N&P leakage.
b) Engineering beneficial microbiomes in aquaculture, with the main aim to increase feed conversion rates and improve fish health that in turn will reduce N, P and organic matter discharge and reduce GHG emissions (CO_2 and N_2O).
c) Engineering ruminant microbiomes with the main aim to reduce methane emission without compromising animal health and ruminant metabolism.
d) Use of tolerant organisms/communities to convert side streams from industrial processes with the main aim to optimize valorization and use of biomasses (more details in section below).

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) understand how microbial communities develop and perform, ii) deploy high-throughput data generation and analyses to assess the composition and modelling approaches, iii) develop modelling approaches that enable prediction of microbiome functionality, iv) develop better precision tools for selective modulation or knock-out of individual microbial species or strains, v) develop sensor methodology for increased speed and accuracy, and vi) develop analytical tools to understand how microbiomes change after precision engineering.

Value inflection points are specific to the different areas covered as some lines of research and innovation have progressed further than other areas. Key overall value 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
The main objective of this workstream is to augment the valorization of side streams in the bioeconomy and is thus closely linked to the above workstream on biorefining. As end products include novel feed solutions, the workstream is also closely linked to the counterpart on microbial engineering. This workstream develops technologies for enzymatic treatment and fermentation of food byproducts and side streams to use biomass fractions that inhere the potential of much greater value creation. While there are shared challenges and goals, enzymatic treatment and fermentation are distinct technologies and the workstream thus progresses on technology development in both fields and across the fields. Key shared challenges include natural variability of side stream biomass, short stability and for some streams, seasonality, as well as logistical solutions for collecting side streams.

Enzymatic based utilisation and upgrading of agricultural side streams and other biomass and algae polysaccharides

Key actions include:

a) The development and implementation of an enzyme technology platform to transform the massive food, agricultural and forestry waste residues as well as algal biomass to precision high-efficiency feeds and valuable food components. Basic research into the conversion of the different feedstocks, enzyme discovery and engineering, enzyme production scale up, basic insight into the interplay of the gut microbiomes of different livestock animals, with the enzymatically processed feedstocks, impact on animal health and mortality, weight gain, enteric gas production. The development of this enzymatic platform will be guided and integrated with in vitro and in vivo analyses of animal and human microbiomes and state of the art enzyme discovery to deliver optimal feeds and high-value food components from low-value waste residues. The impact of this effort in the livestock area will derive from i) lower relative feed demand, ii) lower animal mortality and improved animal health, iii) decreased burden related to manure deposition and storage.
b) In the human food area, the metabolic capabilities of the human gut microbiota to transform the enzymatically processed non-digestible glycans to accessible calories (currently approx. 10% of human calorie intake is derived from the metabolic output of the gut microbiota) and health-beneficial metabolites, will be harnessed. Enzymatic transformation of otherwise metabolically inaccessible structural carbohydrates, to maximize accessible calories, will have a positive climate effect in addition to substantial socio-economic gain via addressing several life style diseases related to low-fiber diets.
c) Mild pre-treatment protocols shall be developed for the feedstocks, new enzymes will be discovered and engineered and enzyme cocktails developed to partially digest feedstocks for high-value feed products. Data on the interplay of new products from waste with the microbiota of animals and humans will be evaluated while the impacts on animal and human health and contribution to reduction of emissions will be assessed.

Microbial upgrade of side streams to value-added products. The overarching aim is to improve utilization and valorization of side streams

› Track D Biotechnology-based food production and alternative proteins sources

Key actions include:

a) To discover and develop new microbial consortia to improve plant-based side streams. Currently, the lactic acid bacteria (LAB) used for plant-based meat and dairy alternatives are dairy-derived and adapted to ferment lactose and not plant sugars. Therefore, there is a need for new and better-adapted strains/starter cultures for fermentation of side streams. These strains should either be non-GMO and Qualified Presumed of Safety (QPS) or they will require an approval from EFSA. It is estimated that 99.9% of microbes have not yet been discovered. Hence, there is huge opportunity to expand the current repertoire of starter cultures.
b) To produce new sustainable solutions for fermentation of raw, processed as well as less processed side streams from the agro, food and feed industries such as brewers spent grains, fruit pulp, sugar beet pulp and rapeseed cake, hereunder to develop new types of food ingredients and beverages based on fermentation of side streams.
c) To extend shelf life of the side streams by fermentation instead of drying, when appropriate.
d) To ensure better taste, texture and nutritional quality of plant-based meat and dairy alternatives. Current plant-based meat alternatives are highly processed and with a long list of additives. The protein content in most plant-based side streams is low and plant proteins often exhibit low quality, poor digestibility and an undesired limitation in essential amino acids: L-Lysine, L-methionine, L-cysteine and L-tryptophan. Further, certain vitamins are present at low levels or are even absent, which may be part of the reason for the vitamin deficiency of people following a strict vegetarian diet. Here fermentation can also be beneficial to the overall nutritional composition, as many fungi and bacteria naturally synthesize vitamins. Moreover, plant-derived products can contain anti-nutritional factors (saponins, phytates and oligosaccharides such as raffinose, stachyose and verbascose) that may be problematic for the human digestive system. Fermentation is a powerful tool for the improvement of the sensory and nutritional properties of plant-based products.
e) To develop high-protein-containing (fermented) plant substrates through tempeh/kimchi-like fermentations of local crops through complex microbial communities.

Value inflection points are specific to different biomasses and technologies. Key inflection points include a database on mapping and characterization 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
The potential is tremendous 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, low trophic aquaculture (LTA) including bivalves, other invertebrates, seaweed, and new marine resources, including non-quota fish, invasive species like Sargasso seaweed or round goby and species occurring in high densities e.g., starfish and shore crabs. The potential extends beyond protein extraction as the biomasses contain valuable compounds such as lipids, vitamins, antioxidants and pigments.

There is a broad spread in the technology readiness level (TRL) of production and extraction technologies as well as for regulatory approval stage of food and feed from the aforementioned biomasses. The commercial maturity ranges from recent commissioning of full commercial-scale production facilities for insects, established use of insects for fish and animal feed, EFSA approval of mealworms for food (January 2021) and an emerging supply chain of process equipment for accelerated growth in the insect industry to proof-of-concept (TRL 4) or below for some of the other biomasses.

There are common gaps in the knowledge for most biomasses of how alternative proteins and other ingredients perform in terms of functionality, including sensory properties, and how this is linked to their structure and composition. Moreover, the knowledge gap on the nutritional quality, the bioavailability of micro- and macronutrients and safety/allergenicity issues must be addressed for most biomasses, particularly when the ambition is for production of food grade proteins and other ingredients. LCA's should be made for all biomass categories.

Key actions include:

Bacteria, yeast and fungi

a) Bacterial protein based on alternative feedstocks such as CO_2, methane or hydrogen oxidizing bacteria is currently produced from fossil resources such as from natural gas, so efforts are required to change to renewable resources e.g.,biogas, while maintaining efficient microbial protein production from such media.
b) Development and optimization of growth media. The growth substrates for cultivation should be sustainable and not compete with feed or food. Ideally microbial growth is done on side streams, however, this entails solving the problem that varying composition may cause uneven product quality and process efficiency. Focus should be on sustainable technologies selective for extraction of sugars and nutrients from side streams with minimum need for chemicals.
c) New reactor configurations for upscaling economically feasible and environmentally sound production.

Microalgae

a) Strain optimization for both phototrophic (CO_2 fixing) and heterotrophic (exploiting side streams) production of desired products. This also includes development of molecular tools for gene editing to alter cell wall composition and enzymatic disruption facilitating efficient recovery of desired products.
b) Develop large-scale fermentation technology and carbon sources for heterotrophic growth, as well as photobioreactor design for phototrophic growth.
c) Further develop the technology to recover and fractionate proteins, lipids, carbohydrates and high-value compounds (bio-refinery).

Lower trophic organism aquaculture (LTA) and new marine resources (Blue biorefineries)

a) For LTA; Optimize the strains for some LTA, further develop the production capacity to reliable methods for large-scale seed production and cost-efficient grow-out methods as well as harvesting and (multi)extraction technologies.
b) For new marine resources: Development of sustainable gear for fishing/harvesting, processing and preservation technology and handling/logistical solutions is needed. The latter three challenges also exist for side streams from seafood production.
c) For LTA and new marine resources: To reach food grade quality, challenges of unwanted inorganic content (shell material),contaminants or trace metals must be resolved.

Insects

a) Optimize insect production to provide nutritionally attractive food and feed items,
b) Document potential beneficial bioactive compounds for animal and human health.
c) Significantly increase the use of insects for animal feed, including fish.
d) Upscaling production in a circular production perspective by feeding insects side streams and utilize frass as fertilizer. Composing diets providing the optimal composition of nutrients based on available and sustainable side stream substrates is challenged by the rudimentary knowledge on the insect's nutrient requirement and nutrient composition of available biomass side streams as well as consumer acceptance of the feed used for insects.
e) Establish nutrient recommendations for insect feed composition,
f) Develop diagnostics and management tools for insect diseases,
g) Identify beneficial insect bacteria associations, and
h) Identify specialized insect species and specialized genetic insect strains targeted specific biomass.
i) Implement alternative insect species or genetic strains with specific properties in e.g., utilizing specific types of biomasses in the Danish insect production.

Green plant biomasses (see also section above on biorefineries which includes grass biorefining)

a) Explore new green biomasses (other than grass) cultivated on marginal land such as halophytes (salt tolerant plants).
b) Process optimization to achieve protein-rich extracts, pure proteins or peptides.
c) Investigate the functional and structural properties and interplay with other components in food matrices.
d) Investigate nutritional and health properties.

Value inflection points vary greatly across and within the above biomass categories. Key generic 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) nutritional 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 is linked to the above workstream on microbial and enzymatic technologies.

Track-specific impact, timeline, and success criteria

The GHG emissions, land use and water consumption from cellular agriculture is 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. Proofs of concept has been obtained and technology platforms in all workstreams have progressed to enable acceleration of i) valorization 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 microorganisms, iii) commercial insect-based feeds are gaining market shares, iv) bacterial protein production from biogas, CO_2 or 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 workstreams. Consumer behavior, preferences, and acceptability 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 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 contributed exports to the amount of 140 b DKK in 2019. A substantial part of the industry is fermentation-based. The Danish food and feed ingredients industry turns over 40 b DKK 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 have a long tradition of utilizing and optimizing 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 characterized 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 optimize 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 foods with a low carbon footprint 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 make 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 incentivize 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 ON LIFE CYCLE ASSESSMENT, DIGITALIZATION AND ECONOMIC INSTRUMENTS

Technologies and land use options that can aid in bringing the Danish agri-food system towards the 2030 and 2050 goals on climate, biodiversity, and nutrient already exist. 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 workstreams: 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 level, 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 workstreams 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 facilitate farmer and industry innovation, develop and adopt new climate and environmental mitigation measures effectively.
- Inducing behavioral 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 behavioral change. This requires holistic approaches and food systemwide collaboration and action.

Key activities in and across workstreams

The three workstreams 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 workstreams constitute a coherent system enabling good governance and self-governance for the agri-food system to undergo a sustainable green transition. The workstream on developing a consistent and credible GHG emission accounting system constitutes an important basis for several aspects of the workstream 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 timeline in Table 10). The full vision includes an integration of both workstreams 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 WORKSTREAM 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 WORKSTREAM TOWARDS 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 WORKSTREAM 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.

TABLE 10 Rough timelime and inflection points.

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 table 10, several successes will be achieved at the different inflection points indicated and implied in the table. We highlight only a few across the three workstreams here.

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 workstreams, 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 table 10.

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. Policy implementation is lagging and is potentially too burdensome for the sector for this to happen. 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 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 crosscutting theme can of course not be seen independently from the qualities of the technologies and behaviors they incentivize. 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 b 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 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_2-eq annually by 2030 and 2050, respectively. Note that this is an impact from coupling governance with the technologies and decision changes they incentivize across all tracks in this roadmap.

CROSSCUTTING ASPECTS
LIFE CYCLE ASSESSMENT (LCA)

While environmental performance of the agri-food sector currently focuses heavily on climate change mitigation, environmental sustainability concerns a whole range of environment impacts that contribute to the local-to-global biodiversity crisis with rapid loss of natural species. Our food production is a main driver behind many of these impacts through its extensive use of land and freshwater, and its releases of nutrients and pesticides and their degradation products to the environment. When assessing the GHG reduction potential of planned innovations and developments, it is essential also to assess the wider set of environmental impacts in order to detect and avoid unnecessary trade-offs between mitigation of impacts on the climate and impacts on the integrity of the biosphere. These impacts need to be assessed for the whole life cycle (or value chain) of food production systems that results from the planned innovations – from the production of auxiliary materials and seeds over crop and livestock production and their processing into food products, their distribution and consumption. Losses along the life cycle are essential to consider as well.

Life Cycle Assessment (LCA) is the tool for analysing the whole value chain and quantifying the contributions to all relevant environmental impacts from the life cycle of food products and agri-food systems. There exist global ISO standards for LCA (ISO 14040 and ISO 14044) and its use for carbon footprinting (ISO 14067) and water footprinting (ISO 14046), as well as European LCA method guidelines that form the methodological basis of LCA, but there are still fundamental methodological choices that require to create consensus in the program. This includes where and how to use attributional (attributing impacts to individual processes or food system components) and consequential (change in impacts as function of a choice or change in the food system) LCAs, how to model the emissions and impacts from pesticides and fertilizers applied in the farming and how to aggregate impacts across the different categories of environmental impact.

LCA can tell us whether an innovation leads to a more environmentally sustainable solution, but it cannot tell us whether the solution is sustainable in absolute terms. With the Paris Agreement, we have set an absolute target for the climate change impacts (70% reduction by 2030, carbon neutrality by 2050) and based on this, we can derive targets and annual GHG emission quotas for food production. To assess the overall environmental sustainability of our innovations and avoid unintentional problem shifting from climate change to biodiversity loss, we must also develop absolute targets, based on biophysical limits of our natural systems, for the other environmental impacts where food production systems are main contributors.

A standardised and consistent LCA methodology must be ingrained in the assessment backbone of the whole activity and inform the research and development activities by supporting benchmarking of the environmental sustainability of the developed new technologies and practices in order to fully achieve European and global ambitions for a sustainable transition of the agri-food sector.

CROSSCUTTING ASPECTS
GOVERNING THE DANISH AGRI-FOOD TRANSITION

Green, agri-food transition governance comprises all the means of exercising control over, steering, and directing the interplay of organizations, institutions, and practices that comprise society's food chains and agricultural systems in the process towards enhanced sustainability. Transition governance is both formal and informal, based variously on legal regulation, power, norms and values, and it requires sustained coordination across spatial (local-global) and temporal (short-, medium- and long-term) scales. Likewise, governance cuts across the public-private divide, by being enacted at the intersection and with the active participation of governments and political agencies, market actors, civil society groups, everyday citizen-consumers, as well as in crosscutting networks and partnerships. Here, non-human ecological entities and processes partake in and frame governance options.

Meeting the combined challenges of climate change, biodiversity loss, and land-system change requires for actors and agencies in the agri-food complex to rethink, redeploy, and reinvent instruments and mechanisms of governance at all scales, local to global, in order to orchestrate far-reaching green transitions (or transformations) of its socio-technical systems. In this process, while technological innovation plays a paramount role, social and cultural conditions and changes are necessary enablers for any comprehensive green transition. The socio-cultural sciences writ largely possesses historically based knowledge and many necessary empirical cases and analytical tools to facilitate and enable the collective learning processes of transition, working in close collaboration with natural-technical sciences and stakeholders.

Historically, Denmark is known for its major coordinated political initiatives that have shaped the agricultural and other landscapes we know and live with today. We have, in the recent and distant past, experienced crises that required major political decisions to mobilize people, technologies, knowledge, and resources on a massive scale, such as the historical Enclosure (Udskiftningen), Reventlow's Peace Forest Ordinance (Fredskovsforordningen), the Heath Society (Hedeselskabet) and following the extensive drainage and plantation projects (Jensen 1975; Løgstrup 2007). As such, Denmark is not in a new political situation. The present rural countryside is equally highly historically conditioned: we are living with major area decisions that were made hundreds, sometimes thousands, of years ago. This includes past collective decisions, which have had major, but also often unforeseen and detrimental, consequences for both human livelihoods, local communities, economies, climate and biodiversity. Today, society needs to learn from these past large-scale coordinated political initiatives and accelerate a socially and ecologically sensitive green transition that

- builds on trust, involvement, adaptability and co-creation
- include human-nature relationships
- is inclusive and fair, locally and globally

TRUST-BASED, INVOLVING, AND ADAPTIVE TRANSITION MANAGEMENT

At the heart of agri-food transition stands a collective action problem: whereas the collective benefits in terms of health, climate, biodiversity, and upscaling of economic niche innovation stemming from a shift toward a more sustainable (including more plant-based) agri-food system are scientifically well-established (Prag & Henriksen 2020) and starting to be widely known, still few individual entities along the relevant value chains have sufficient incentives to change habitual behaviors and practices. Transition requires governance to change this vicious circle of lock-in into a virtuous circle of trust-based, involving, and adaptive change across the agri-food complex and society at large. Such a process hinges on facilitating practice-based learning and co-creation among all relevant private, public, and non-profit stakeholders, as well as broad-based dialogues with citizen-consumers to accelerate change in collective norms, behaviors and practices (Nyborg et al. 2016; Herrero et al. 2020). At all stages of this process, reflexive evaluation, monitoring, and learning should take place, as part of addressing tensions and building shared understandings among stakeholders and to enable continual adjustments to practice and visions (Loorbach 2010).

In setting up transition pathways, stakeholders and researchers should take as point of departure the considerable body of knowledge already available across the socio-cultural sciences on the dilemmas, constraints, and possibilities faced by actors across agri-food value chains. At the level of consumers, for instance, there is solid evidence showing how established dietary habits, lack of skills and knowledge on healthy and more plant-based diets, and perceptions of undesirable taste among large consumer segments, remain barriers to the wider diffusion of what is today niche plant-based food products (Graca et al. 2019). Moreover, research into behavioral and everyday practice change among citizen-consumers has shown that governance works best when combining tools from across three types of intervention: price incentives and choice environment design targeting individual choices; food guidelines, public procurement policies and other initiatives targeting social norms and peer acceptance; and the practice-near provision of new skills, knowledge, and materials targeting the level of everyday habits and convenience (Keller et al. 2016).

Similarly, research documents how farm-level decision-making is framed by a combination of factors, including formal rules and standards, market and supply chain forces, questions of legal liability, social networks and norms, as well as available technologies and the science-based advice carried by agricultural consultants (Baur 2020). Governance must seek to address these institutional dimensions of constrained farmer choices, including via sustainable financing mechanisms. More generally, policy research suggests that smart regulation can facilitate norm change (Nyborg et al. 2016), including by supplementing traditional supply-side agri-food policies (e.g., EU's common agricultural policy) with more hybrid and demand-side measures (Daugbjerg & Feindt 2017). Here, the cases of organic and meat-substitute products suggest that large retailers and public procurement via its canteens, in particular, can play important roles (Tziva et al. 2020). Also, it matters for public receptiveness how agri-food policy measures are framed, in terms of appealing to public health, animal welfare, or environmental benefits (Whitley et al. 2018).

Some of the pathways of the sustainable transition of the food sector towards the 2030 and 2050 goals are known but primarily in terms of knowledge on general measures and technologies for shifting producer and consumer behavior. Thus, in order to ensure e.g., a more (climate-, biodiversity and species-) sensitive plant and animal production substantial challenges exist both in identifying and conceptualizing relevant transition pathways based on existing knowledge, and to include new insights and possibilities that emerge during the transition process. This involves identifying and conceptualizing implementation pathways and roles for producers and consumers and giving suggestions to the supporting policies, technology development and relevant financial models.

In implementing and gradually adjusting appropriate top-down policy mixes, an interplay should be established also with bottom-up civil society experiments, which provide practical knowledge and critical questions for markets and policies to take on board in a process of reflexive institutional learning (Eckersley 2020). Moreover, it is paramount for processes of technological innovation to facilitate broad-based public deliberation and involvement, in order to foster trust and ensure that socio-technical transition pathways remain locally appropriate and responsive to local development aspirations.

A GREEN TRANSITION THAT THINKS HUMANS AND NATURE TOGETHER

We need to, secondly, ask ourselves what makes a good green transition, that is, what collective values it should harbor and express. The landscape models promoted must meet a range of different needs and values besides from the four bottom lines (of people, profit, planet and progress). In addition, we need people at all levels in society to take the lead in this, not only in terms of demand, but also in terms of governance and value creation.

The green transition will challenge the prevailing view of nature, including taking for granted life and species hierarchies (Povinelli 2016; Tsing 2018). A green transition involves a switch from seeing humans as consumers, producers and nature destructors to protectors, governors and responsible co-creators (Descola & Pálsson 1996). It is based on a radically non-hierarchical view of nature, where culture - and essentially humans - are not seen in opposition to nature, but as responsible and also necessary for nature management and conservation with a view to biodiversity and crisis prevention due to imbalances in the relationship between man, animals, plants and nature. Nature experience, nature conservation, and natural wealth are values that presuppose clear and democratic interventions, governance and institutions.

In order to reduce and ultimately reverse the so-far increasing distance between humans and other species, as well as between consumers and the agricultural sector, more biodiverse and mosaic landscape vegetation structures should be encouraged, where humans and livestock act as nature managers and conservers. (Pre)historic and present-day cases of polyculture and landscape mosaic production systems, such as heath farms, permaculture and rotational cultivation, can form vital inspiration for sustainable forms of governance and integrated human-nature systems (Fagúndez 2013; Woestenburg 2018). These combine and build upon high-intensity and low-intensity production land as well as a range of different kinds of ecologies, including pastures, croplands, fallows, forest and meadows and ecosystem services.

More generally, landscape mosaics point to the fact that nature does not have to be either enclosed or taken completely out of production systems in order to be protected. Exploring alternative production forms could imply developing alternative agricultural business and management models (e.g., heath farms) and associated technologies, including rotational grazing and herding, removing drains, nitrogen redeposition and reforestation. There is international inspiration (e.g., from UK and the Netherlands but also from Asia, Africa, Latin America, Oceania) to be found in small-scale examples for use in nature (re)creation and combining nature conservation (e.g., NATURA2000) and cultural heritage protection. However, Denmark is in a unique position to become an international lighthouse inventing and developing models of socially, culturally, and ecologically integrated landscape governance.

Landscape use and production systems as conservation can be scaled: it means that, even on the larger global scale, we must ensure a global balance in the green transition and make this transition fair to achieve social security. There will be a special focus on both densely populated and sparsely populated areas, both on green cities and landscape management. Solutions can accommodate skills development, education, digital platforms or other digital tools for use in peer-to-peer exchange or other citizen-engaging projects, where solutions arise on a small scale rather than on a large scale. Furthermore, research must be done into understandings of human interaction with nature and other animals in a new light with a connection to e.g., global health and the risk of new pandemics.

In short, a national and globally embedded green agri-food transition will inevitably involve comprehensive and collective value shifts that are not only related to biodiversity or humans' relationship with nature, but which will also influence livelihoods, beliefs, and identities on multiple levels. As a society, how do we create a space for discussing these issues? How do we meet in these dilemmas? How do we imagine sustainable future landscapes and 'talk green'? We need governance processes for acknowledging, balancing and handling dilemmas, conflicts, conflicting values and considerations that will arise rapidly and over time as well as finding ways of working together across differences. The historical, archeological, and cross-cultural knowledge of the humanities attains here a key role in interdisciplinary collaborations.

A FAIR AND DEMOCRATIC TRANSITION BASED ON LOCAL CO-CREATION

Finally, more research is needed on how to drive a transition that not only builds on but also fundamentally promotes a sustainable society with social justice, cultural viability, and global balance for the benefit of both people and nature. Here, stakeholders and researchers should build on but also move beyond established commitments to user involvement in technology-oriented living labs, landscape management as well as established practices of citizen and stakeholder involvement in planning and policy-making (Bulkeley & Betsill 2015; ENoLL 2006). Moving further in the direction of fairness-oriented and democratic co-creation promises not only a better chance of delivering on ambitious environmental targets by facilitating collective learning, but also to revitalize local economies, address rural-urban divides, and further social cohesion (Franz et al. 2015).

First, significant landscape changes and land redistributions must be accompanied by carefully organized participation of involved and affected citizens and stakeholders with a special respect for land tenure rights. Models for involving local citizens and affected parties – including representatives of non-human species – in the planning and management processes is an indispensable part of the agri-food transition (McGreavy et al. 2016). This process may be played out in various ways on multiple scales, and will be stretched out between formal and informal procedures, and between property right claims, citizen participation and knowledge-based justification. Investigation of experience with cutting-edge stakeholder involvement experiments is needed in order to establish a solid local basis for planned landscape changes, where the wishes and future plans and aspirations of local property owners and citizens sit center stage.

Second, living labs constitute a widely acknowledged methodology for fostering the kinds of stakeholder-inclusive technological innovation that sits at the heart of agri-food transition. At the same time, however, stakeholders and researchers should realize the gap between two important types of living labs - the user-centered and the citizen-centered, respectively - both of which should play key roles in the transition, yet in complementary ways (Gamache et al. 2020; ASC 2016). User-centered living labs are techno-centric and market-oriented, serving as testbeds for new technologies and product design, by way of involving farmers, scientists, and civil society actors in the process of finding solutions and spurring early market adoption. Citizen-centered living labs, by contrast, are oriented to a broader and more holistic sense of local development, seeking to foster citizen-consumer empowerment and transformative learning as part of building more sustainable local communities. In Denmark, the cooperative movement tradition may be said to have relied on building strong ties between these two types of living labs, serving as inspiration also for future-looking transition.

Third, and relatedly, green agri-food transition creates a need for enhancing rural innovation capacities by way of revitalizing rural territories and policies (Carstensen & Bason 2012) - as well as ways of (re-)connecting rural-to-urban value chains as one way of fostering lower environmental footprints and quality of life in green cities (Banzhaf et al. 2018; Houlden et al. 2018). In the context of sectoral shifts and the decline of the relative importance of agriculture and forestry in the rural economies of Europe, agricultural employment has dropped considerably, also in Denmark, driven largely by productivity increase. New activities have developed in rural economies, including tourism, small-scale and niche manufacturing and food production and business services. However, the food security agenda and the increasing demand for biomass for a variety of bio-based applications have again raised new interest in the economic opportunities related to primary production and the associated food and non-food value chains. This new interest is combined with stakeholder concerns over the capacity of rural areas to cater sustainably for all these needs while providing essential ecosystem services, amidst increasing urbanization (and soil sealing) and the pressure on land resources caused by climate change. There are also important questions around the impact that different types of value chains or renewed urban-rural linkages could have on local development and job creation. Evidence and knowledge should help policy-makers overcome such challenges and seize new opportunities, by helping them to develop the most appropriate governance approaches.

Ultimately, locally appropriate responses to and pathways for green transition need not only address questions of local social fairness and inclusiveness, but also to remain responsible to the wider global context of environmental and intergenerational justice. Overall, the collective action problems of climate and biodiversity are indicative of how societal decision-making processes have tended so far to remain insufficiently attuned to this global, long-term perspective. Amidst the need for a far-reaching collective learning process across diverse and sometimes conflicting values, not everything about the agri-food socio-technical transition is at present amenable to a linear or science-based planning approach. Inclusive, fair, democratic, and adaptive procedures of transition governance are needed to ensure the necessary societal commitment to turn present-day vicious circles into the virtuous circles needed to reach the green transition sustainability goals of 2030, 2050, and beyond.

CROSSCUTTING ASPECTS
CLIMATE AND RESOURCE-EFFICIENT FOOD PRODUCTION

Food processing is not an isolated island but an integral part of the supply chain from farm to fork with the overarching goal to deliver attractive foods products and ingredients preferred by consumers and customers. The theme of climate and resource efficient precision food processing focusses on disruptive and innovative post-harvest treatments of "harvested" commodities and cuts across all sectors, i.e., animal-based, plant-based, and biotechnology-based food production and alternative protein sources. The goal of precision food processing will be achieved through researching and developing technologies that allow implementation of circularity in food processing value chains to eliminate waste of raw material, reduce use of water and increase use of renewable energy sources, with an end-goal of providing healthy and nutritious foods with a documented, minimal carbon footprint.

As humans, we eat diets – usually consisting of a mix of product categories (e.g., vegetables, fruits, meat, fish, and dairy products) and products that have been processed more or less before reaching the consumer or customer (e.g., food service/catering), where the final processing/preparation takes place. It is important to keep in mind that the raw material quality is critical to the food processor and needs to be considered when producing the crops, carcasses, milk, berries, etc. Furthermore, the quality of the processed foods is important for the consumer/customer. Hence, strong links exist between different parts of the food value chain. For a review of different perspectives on quality, please refer to Kidmose et al. 2013. Complete usage of the resource including side streams is a prerequisite for sustainability. Consequently, it is essential to take a holistic, circular approach when designing climate and resource efficient food processing.

Vision

The starting point is recommendations no. 17, 18, 21, 23 and 24 in "Klimapartnerskabet for Fødevare- og Landbrugssektoren", with a clear recommendation that research, development and demonstration activities should be initiated targeting water efficiency and transformation of the food processing industry towards electrification and higher energy efficiency and reducing side streams and waste by increased utilization of raw materials and extension of product shelf life. Thus, the food processing industry will contribute substantially towards the goal of a 70% reduction of climate gases, etc. by 2030 and being climate neutral by 2050. Furthermore, the industry will develop climate and resource efficient processes, products, technologies, and knowhow with high impact on a global scale and ensuring future Danish competitiveness in the international marketplace.

Objectives and goals

The objective of this crosscutting theme is to perform research and develop technological solutions that – when implemented in the industry supply chain – will convert conventional food processing companies into resource-optimized, sustainable and climate neutral operators.
The specific objectives are to:

1. Identify and implement technical solutions, including electrification of industrial processes, to reduce CO_2 emissions by 50%, improve energy efficiency by 30%, and improve water efficiency/reduction of water use by 15-30% compared to baseline 2020.
2. Reduce side streams and waste by increasing utilization of raw materials – e.g., valorizing nutrient-rich side streams, and upgrading waste to valuable products and ensuring that products are not wasted e.g., by improving shelf life of both raw materials and end products. This will have an estimated annual value of 500 m DKK or a total reduction potential of 218 ktons CO_2e (Klimapartnerskabet for Fødevare- og Landbrugssektoren, 2020).
3. Develop new products, processing concepts, technologies, sensors, and digital solutions as well as implementing best practices to increase resource efficiency, competitiveness, and export of food, technology, and know-how.
4. Map, develop, and implement tools and technical solutions to recycle or reclaim nutrients, energy, and water streams within the processing plant and to improve "green processing" branding possibilities towards consumers, customers, and present and future employees as well, leading to increased competitiveness, job satisfaction and job retention.

The goals will be achieved through use of green and efficient technologies that allow implementation of circularity in food processing value chains to reduce waste of raw materials, and water and energy consumption.

Furthermore, processing and product quality are controlled by multi-level analytics, process analytical technologies along the production chain – again to ensure that raw materials and products are not wasted, and side streams are minimized.

Looking at animal food products, the main climate impact is in primary production. However, the value chains are complex, and a significant climate improvement requires a rethinking of all links and connections in the value chain to be sure that improvements in one link are not lost in a later one.

Meat and dairy play a role in a balanced diet and are crucial nutritious products easily available to the consumer. However, the global demand for animal food products needs to be met by competitive production systems with a low GHG emission. Undoubtedly, the diet consumed in the Western part of the world should be altered to include more plant-based products. To ensure this transformation, focus must be on reducing waste (increasing shelf life and ensuring food safety) in the value stream and developing parameters such as taste and texture, to ensure that the new plant-based products will be acceptable to a broader audience. The use of plant materials from land and sea, or raw materials that do not use land on formulation of food products requires new technological approaches and development of novel sustainable plant-based ingredients. Enormous resources exist in land and sea, but more than 44% of the harvested crops' dry matter is lost prior to human consumption (Alexander et al. 2017). Agricultural residuals, e.g., leaves, roots, skins – which are not digestible, but high in nutrients and flavor – account for ~60% of this value. Furthermore, production of one product, e.g., oil or starch, leads to protein rich streams being underutilized. Current technologies to produce plant-based ingredients are disconnected from the production of the final plant-based foods, they cause significant nutrient losses due to over-processing, and require large amounts of water and energy (van der Goot et al. 2016). Thus, sustainable approaches to processing of plant raw material have a significant potential to reduce environmental impact, increase global food security and support the creation of healthy and sustainable plant-based food products.

Examples of concrete research and development goals are:
Sustainability and energy optimization

- Electrification of all processes to replace black carbon with green energy.
- Developing more energy and cost-effective production processes.
- Replacing indirect heating operations with novel direct heating technologies to reduce energy consumption, resource, and losses, e.g., support the implementation of sustainable heating technologies using direct heating (e.g., heat pump, ohmic heat, microwave, RF, infrared) in a manner that ensures food quality and safety.
- Establishing new refrigeration and freezing technologies with reduced carbon dioxide footprint and rethinking evaporation and drying for more sustainable and functional products.
- Implementing non-thermal technologies to support process intensification and improve product functionality.
- Developing sustainable technologies like membrane filtration, super critical CO_2 extraction, and flocculation for recovery of valuable components from side streams.
- Developing sustainable technologies to produce protein-rich ingredients from plant raw materials or their side stream based on gentle processing approaches for extraction, fractionation, functionalization, and stabilization.

Sensor technology, digitalization, and process analytical technology (PAT)

- Developing sensor and digital solutions to enable precision food processing for optimal product quality and safety and to avoid waste.
- Developing fast methods (e.g., rapid image/sensor data analysis and deep learning on process data) for the optimal use or sorting of raw materials prior to processing.
- Developing novel data acquisition methods for end-product quality assessment.
- Merging process analytical tools (PAT) and artificial intelligence (data science) tools to obtain new production management and control systems.

Supply chain and logistics

- Developing new or optimized process technologies and production flows to make sure that the full nutritional potential of the raw material is utilized and preserved, to include post-harvest technologies to ensure food supply throughout the year.
- Researching processes and technological approaches to extend shelf-life and/or improve safety or functionality of food or ingredients.
- Developing tools to map resource savings and effect on environment (eco-efficiency).
- Optimizing water economy, including reduced use, recycling, treatment, quality, and cleaning operations.
- Looking into technologies to recover and upcycle side streams to reduce waste.
- Developing robotics to improve harvest/slaughter and post-harvest operations and support the initial stages of raw material processing.
- Exploring biotechnological approaches (microorganisms and/or enzymes) to extend shelf life, reduce food waste and improve sensory characteristics.
- Reviewing several aspects of supply chain and logistics management in the pre- and post-production stages, addressing issues such as forecast-based production instead of demand-based and programs that establish traceability and transparency towards the consumer.

Current challenges and gaps

TECHNOLOGICAL
It is estimated that the food processing industry in Denmark currently emits 1.7 m tons CO_2, as it spends energy amounting to 15 PJ (1015 J) from fuels and 8 PJ from electricity (Elmegaard et al. 2021) as well as large volumes of drinking water (>70 m m^3 per year). On top of that it is estimated that food components amounting to a value of 1,000 m DKK are lost in wastewater or unrecovered side streams and due to production inefficiencies/production loss (i.e., downgrades).

Below is listed current challenges and gaps in relation to climate and resource-efficient food processing. Some topics are easy to implement (low-hanging fruits with little or no R&D required), whereas others require multidisciplinary R&D efforts.

Sustainability and energy optimization

- Indicators of sustainability in food systems need to be mapped and evaluated across multiple domains (i.e., food safety, waste, resilience, nutrition, environmental resources and land use, fossil fuel depletion) (Chen et al., 2019). The food components which are lost as wastewater, in unrecovered side streams or due to production inefficiencies and/or product loss (i.e., downgrades) need to be mapped.
- Direct heating: A relatively slow growth has been noted in the number of industrial installations due to lack of experience of equipment manufacturers to designing processing equipment for the food industry's specific needs. Also, the demands of regulatory approval place a burden on first movers.
- Refrigeration and freezing: Capitalize on advances made around refrigeration and freezing technologies, providing comprehensive solutions to current scientific and technical sustainability challenges associated with energy reduction along a food chain whilst maintaining quality, safety and shelf-life of food products, e.g., to reduce waste due to defects caused by microbial and enzymatic activity.
- Rethinking thermal processing such as evaporation and drying: Pre-processing and combination of technologies can make energy usage more effective, reduce CO_2 and reduce potable water usage. Non-thermal technologies, either as alternative pasteurization techniques or as processing aid, have shown potential not only to support the shift to CO_2-free processing but also having a potential to improve product quality and safety.
- Limited knowledge is available to produce protein-rich ingredients to replace animal proteins, and current industrial practices of isolating and concentrating plant proteins into components that can be used as alternatives to e.g., soya, generate significant water waste, energy, and nutrients. The typical yield of a current wet protein isolation is between 40 and 70%, with an estimated 44-48% of the equivalent CO_2 emissions attributed to the isolation process. The overall result is that the equivalent CO_2 emissions are only slightly lower than those from the production of pork or poultry (Boom 2019. EFFOST Congress, Rotterdam).

Sensor technology, digitalization, and process analytical technology (PAT)

- Sensor technology: In-line rapid multivariate measurement techniques for bulk and targeted chemical species quantification – such as water content to optimize drying processes, or cleaning agents used to optimize resource use in CIP and SIP cycles ("When is it cleaned enough?"), or accumulated compounds (even at trace levels) in circular loops.
- Process analytical technology: Process analytical tools for optimization and process management to minimize waste as well as water and energy consumption, and at the same time optimize quality, safety, yield, and eco-efficiency, are highly complicated especially when closing the production loop and valorizing side streams. To facilitate the management of novel measurement and digitalization technologies and improve circularity in the use of resources, it is necessary to conduct research in predictive models, digitalization, and sensor technologies (process analytical technology) to clarify the exact amounts of resources needed to process the food for optimal yield and desired quality, without compromising safety.
- Process analytical technologies have been successfully applied with respect to animal-based products; however, so far, the technologies have been applied to a lesser extent when it comes to application in plant-based raw material processing. Focus should be on this to improve product and process performance.

Supply chain and logistics

- Food production is currently based on forecasts instead of demand due to lacking standards for information exchange in the retail supply chain leading to increased inventories, waste, and lead-times. There is a need to develop and test new improved information exchange standards and machine learning techniques to utilize the unused information (e.g., using discrete simulation models). As customers ask for more product information including transparency and traceability, an industry-wide initiative to design and test an information sharing (block chain) portal to enable suppliers, processors, and retailers to share and document information with customers (origin, product characteristics, life cycle assessment, etc.) is needed.
- Processing approaches and technologies for plant-based raw materials: Large-scale processing of plant-based raw materials is currently limited to few crops, and valorization of their side streams rich in nutrients is limited to few successful applications for food although byproducts are largely used for feed. Technologies are in general limited to few traditional processes that consume significant amounts of energy and water for washing, thermal processing and drying. Analytics, modelling and process analytical technologies processes are lacking, and processes have been optimized towards yield that do provide sufficient information to reduce CO_2 emissions or control food processing operations towards product properties relevant for end-users, such as stability, functionality, bioavailability of nutrients, texture, flavor, and taste. Over-processing, in addition to a loss of resources, also leads to failure in structure, loss of water-holding capacity resulting in the need for adding structure-forming agents, such as stabilizers and thickeners.
- Gentle processing technologies: New, low energy-consuming approaches are needed based on enzymes or fermentation technologies to gently treat the plant-based raw materials and improve the extraction processes, decrease the presence of antinutritional components and unwanted taste and colors, and improve the digestibility or flavor profile of the raw material. Selection of plant-derived lactic acid bacteria and control of novel fermentation processes is necessary to control pathogenic bacteria during the process. Fermentation and enzymes may also be used for animal-based products for instance to speed up maturation or extend shelf life, thereby reducing cooling and storage cost and reducing waste by extending shelf-life.
- Digital twins and the use of mechanistic models coupled with chemometric/machine learning systems is used to make a "twin" or parallel simulation of the food processing. Information regarding the environmental conditions and treatment of the raw materials are stored in a digital twin, e.g., plants can be harvested according to individual processing requirements. This enables a feedback loop for artificial intelligence where quality of the final food products is connected to the growth conditions of the plants, the conditions of the animal and milk production, etc. Automated robotic systems with novel manipulators (e.g., soft robotics) can gently process plants during and after harvest, e.g., cleaning or sorting side streams for further use.

IMPLEMENTATION
There is a need to create pilot plant infrastructures to support design of equipment, to develop processes and for assessment of products. Increased collaboration between universities and industry, including farmers, technology providers, ingredient producers and food industry is needed. There is a large potential for SMEs to find new business opportunities and for creation of new companies.

Sustainability and energy optimization

- Electrification of the industry to reduce or eliminate the reliance on fossil fuel, is in its infancy with mapping begun in some segments. The potential for higher energy efficiency is based on efficiency measures, process integration between heating and cooling demands by direct heat recovery and heat pumping and by electrification by means of other technologies substituting heating completely. The potential for electrification is determined to be on the order of 60%, which would decrease the use of fossil fuels to a few percent only. In some cases, full electrification of the production is estimated to be an option leading to expected action among industrial first movers within the next few years (Elmegaard et al. 2021).
- Heating: Several novel and radical technologies, e.g., Ohmic heating, MVR technologies, microwave drying systems, IR, direct steam injection have been proposed to replace currently used technologies. However, research and development are needed to move technologies from the proof-of-concept stage into operational technologies in an industrial setting. Ohmic heating has already been developed for liquid foods where stirring is possible, however for solid foods like cooked ham or sausages, no technology providers have yet succeeded in developing ohmic heating. Heat mapping, changes in heat transfer and kinetics will have profound consequences on quality, functionality, and safety of the product. Therefore, the appropriate data and design feedback is required to ensure innovation, and to provide the necessary information and documentation for market and consumer acceptance and for regulatory approval.

Sensor technology, digitalization, and process analytical technology (PAT)

- Process analytical technology: Industry-wide adaptation of machine (deep) learning model systems for interpretation of system performance, to identify adverse unit operation performance or bottleneck, or aid in cross-production system resource optimization, is still lacking. So is the use of mechanistic and/or hybrid models coupled with chemometric/machine learning

systems used to make a "twin" or parallel simulation of the process to e.g., determine if the correct levels of microbial inactivation have been reached.
- Data science and predictive systems: The role of data science in optimization of manufacturing systems has seen an explosive development the last decades. Traditional processing predictive models have been done through application of classic multivariate data analysis. An immediate application is to develop novel process optimization strategies by combining in-line measurements and data analysis such as deep neural networks that allow precision processing towards safety or quality aspects. Such rapid diagnostic tools are needed to predict qualities. As an example, proper sorting will allow proper milk to be used for UHT products and thereby avoiding waste, as enzymes from microorganisms may exert quality defects due to heat treatment survival. These defects can lead to significant waste during storage and export.

Supply chain and logistics
- Sustainable and cost-effective technologies for extraction of components from solid as well as liquid side streams and converting them into valuable products are needed. As an example, organs and blood contain proteins of high nutritional value. However, it is still a challenge to obtain a colorless protein product with high functionality and without off-taste.
- New processing approaches and technologies are needed to produce plant raw ingredients that match the required safety, functionality and nutritional value while promoting circularity by valorizing side streams. New sustainable Nordic crops are being developed, cultivated, and need to be transformed into added value products through sustainable processing. New cultures and enzymes will be identified to improve ingredients and food products as well as production processes. Furthermore, analytical tools and robotics needs to be developed, demonstrated, and implemented.
- Cleaning: More than 70% of the potable water consumed in the industry (in Denmark annually >70 million m^3) is used in cleaning operations to maintain a hygienic environment suitable for safe production. Progress in water purification technologies could allow the industry to significantly reduce their water consumption (and hence also emission of wastewater) by treating and reusing the water. However, several barriers exist including lack of knowledge about suitable water qualities, monitoring systems, regulatory and customer acceptance, and long-term effect on the food quality and safety.

FINANCIAL
When it comes to food processing, the different sectors may leverage each other, and knowledge may be transferred from one production system to another. Furthermore, some of the challenges are shared across the board and may be solved in a joint effort, hence reducing the collective cost and work effort.

Implementation of radical and novel technologies places a burden on the industry, especially if it is unproven technology where its success, its consequence on the product performance and quality and pay-back cannot be entirely predicted. For example, the design and implementation of a water treatment system to treat spent process water for reuse in the cleaning of the food processing facility (more than 70% of all water consumed in a typical plant is spent on cleaning) seems a straightforward preposition. However, research is needed to define what constitutes the "right" water quality and if treatment lives up to the expectations and justifies the investment.

Challenges related to a change from current evaporation, heating, and drying technologies from steam to electrical heating are tied not only to product quality but also compliance with regulations and demands from export markets, but also present an untapped opportunity to create appropriate well-targeted technologies which would be adopted worldwide. Innovation in equipment design comes with a significant financial burden and delay in implementation for the technology developer and the first movers within the industry to create the documentation that is required for regulatory approval of disruptive technologies. The capacity of the electrical power supply may also need to be reengineered to meet the demand by an electrified industry. Lastly, tax incentives could also play a key role in implementation of solutions with a low GHG emission. The industry is rapidly accelerating towards fully digitalized productions, yet a lot of data and knowledge acquired is stored but not utilized for any purposes. These data stores can become quite valuable when used in tandem with logistic/supply-chain and production paradigms (quality by design through PAT) that can utilize the data. The data stores can potentially be the leverage that relieves the investment burden for the industry for investing in new sensor technology and production methodologies.

Growing consumer consciousness towards meat and dairy substitute products is stimulating the plant-based ingredients market growth, that is expected to grow at 8 % CAGR to 13.7 b USD by 2021. The plant-based ingredients market share is competitive and fragmented – shared internationally between IFF, Roquette, Cargill, Dohler Group, and Naturex. Despite a large potential, limited production is done in Denmark. In addition to CP Kelco and KMC, ingredients suppliers in the plant-based space are emerging in Denmark, e.g., Cosucra (pea protein and natural dietary fiber), Organic Plant Protein, Vestkorn, NISCO Plantmade (peas and fava beans), seaweed (Nordisk Tang, Dansk Tang), and Agrain (brewery spent grain). Most of the manufacturers are building strategic collaborations to developing new products, as significant technical challenges regarding functionality, taste and nutritional value of these ingredients remain unsolved. Large investments are needed to speed up the development of sustainable and innovative processes, equipment, cultures and analyticals for production of plant-based ingredients from lab-scale to pilot and industrial scale. Furthermore, demonstration activities and strong collaboration between industrial partners and academia are needed.

Strongholds and potentials

DESCRIPTION OF ACTORS
The industry is already taking many incremental steps to reduce consumption of water, energy, and resources as such. However, more radical technology advancements are needed to reach the ambitious goal. This requires a triple helix partnership, where academia, industry, farmers and authorities work closely together to generate economic and societal development.

The challenges may not be solved through one university:one company projects but requires a partnership between multiple partners with different competences to produce bold solutions to difficult industry and societal challenges.

The partnership should focus and accelerate research and development within sustainable industrial food processing, with the ambition to save resources, while at the same time taking climate, environment, hygiene, food safety and consumer preferences into account.

Universities provide radical solutions and insights; GTS institutes facilitate the translation of research into solutions ready to implement. Food & Bio Cluster Denmark facilitates networking opportunities and acts as a strong motor pushing the results to a broad range of end users – both nationally and internationally.

Technology providers/companies provide technology know-how, understanding of food processing and novel solutions. Food producers provide the burning platform (climate, energy, water, other resources) and a deep understanding of own production set-up. They also provide a continuous improvement platform with management attention.

Authorities are involved to safeguard implementable solutions and help pave the way for solutions that need approval prior to use. Involving authorities early on will be beneficial for all parties and will reduce resources spent on solutions that may never have a chance of reaching approval at national or international level.

As is evident, this conversion of the food processing industry is no small feat and will require a multidisciplinary and holistic approach and a close collaboration between researchers, process designers, product developers and industry from a wide range of disciplines and professions, along with the relevant authorities. However, the Danish competence level is high in most of these areas and the partners have a long track record of working together for the benefit of all.

DESCRIPTION OF RESEARCH AND TECHNOLOGY POSITION
The food industry partners face numerous challenges towards the conversion to becoming independent of the black energy, optimize raw material utilization and reduce water emissions and food waste. It is possible to re-engineer the 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.

Denmark has an enormous potential to achieve a leading position fast with an advanced agricultural sector and a strong ecosystem of ingredient companies to provide cultures and enzymes, equipment suppliers, suppliers of analytical tools, and many food producers. Furthermore, as some activities are in their infancy, the development of new business models, start-ups and small and medium-size companies will clearly have an important role to support the development of this sector. Below is a list of potential, relevant partners – please note that the list is non-exhaustive.

Several companies are starting up or establishing production activities in Denmark to produce plant-based ingredients. There are significant differences in the technology position depending on the type of crop or side stream to be processed. The technological challenges are very different depending on the crops or side streams, ranging from processing technology challenges (e.g., low yield), to poor ingredient functionality (e.g., solubility or water holding), or low digestibility (e.g., antinutrients).

EXAMPLES OF POTENTIAL PARTNERS
Danish universities: University of Copenhagen, Technical University of Denmark, Aarhus University, University of Southern Denmark, and Aalborg University.

International universities, including: E.g., Technical University of Munich, Germany, Lund University, Sweden, and Wageningen University, The Netherlands. EFFoST and FoodForce are also strong European networks.
GTS institutes, including: Danish Technological Institute, Force Technology, and Alexandra Institute.
Ingredient suppliers, including: Chr. Hansen, Novozymes, KMC, IFF, CP Kelco, Hamlet Protein, Arla Foods Ingredients, Essentia Protein Solutions, Cosucra, Organic Plant Protein, Vestkorn, NISCO, Crispy Food Nordic, Agrain, Plantmade, and Naturem.
Equipment suppliers, including: GEA, SPX, SiccaDania, MMS, Tetra Pak, Sani membranes, Aquaporin, Grundfos, UltraAqua, Frontmatec, SC Nordic, and start-up companies.
Suppliers of analytical tools and services, including: FOSS, Grundfos, Videometer, IH Foods, and Eurofins.
Food companies, including: Thise, Arla Foods, Danish Crown, TripleNine, Lantmannen, Orkla Foods (Naturli), Planteslagterne, Simple Feast, Easis, LikeMeat Nordic, Carlsberg, Royal Greenland, and start-up companies.
Stakeholder organizations, NGOs and others: Plantebranchen, Dansk Vegetarisk Forening; Danish Agriculture and Food Council, The Danish Food and Drink Federation, MADE - Manufacturing Academy of Denmark, and FoodNation.
Authorities, including: The Danish Environmental Protection Agency (Miljøstyrelsen), The Danish Veterinary and Food Administration (Fødevarestyrelsen), and The Danish Energy Agency (Energistyrelsen).

Concrete goals

Goals for 2025
- By 2025, increased utilization of raw materials – e.g., optimal utilization of raw material and reduction of food waste, upgrade waste to valuable products and extraction of valuable residual matters in process water, leads to gains of an estimated annual value of 500 m DKK – this is expected to increase to 2 b DKK in 2030. Competitive industrial production of high-quality plant ingredients has been established in Denmark.
- Knowledge regarding the potential of new crops and side streams for ingredient production is growing.
- Potential cultures and enzymes for gentle processing have been identified.
- Analytical tools and digital twins are widely applied during milking, slaughter, and processing of animal-based products.

Goals for 2030
- By 2030, processing of food and ingredients has been converted (e.g., by implementation of novel technical solutions, electrification) to reduce CO_2 emissions by 70%, improve energy efficiency by 50% and water efficiency/reduction of water use by 30% compared to baseline 1990.
- At least five Danish companies are producing industrially high-quality ingredients, and export of the ingredients has increased by 20%.
- Mild extraction and fractionation processes for plant-based ingredients have been implemented.
- Culture and enzyme solutions are available for improving taste, nutritional value, and functionality of different food groups with special focus on plant-based products.
- Multi-level analytics and process analytical technologies for designing, analyzing, and controlling processes have emerged to ensure quality, safety, and functionality.
- Analytical tools and digital twins are widely applied during harvest, slaughter, and further processing.

Goals for 2050
- By 2050, a firmly engrained mindset in the industry to use a circular approach has facilitated the achievement of net-zero emissions in the food processing industry.
- Novel robust processes, based on enzymes or novel technologies e.g., robotics, to gently recover valuable compounds from plants and side streams have been developed.
- A diverse mix of sustainable and climate-friendly high-quality ingredients and products from both plant and animal sources have been developed. Denmark has a leading position in international trade. The Danish products each contribute to a sustainable, healthy, affordable, and culturally acceptable diet.
- Equipment solutions, robotics, cultures, and enzymes produced in Denmark are exported in vast numbers.
- Robotics, PAT, and sensor technology are widely applied during harvest, slaughtering, and further processing.

Impact on the strategic goals and value creation

EXPECTED IMPACT OF KEY ACTIVITIES
The expected impact of key activities includes – but is not limited to:

- Development of new products and ingredients, 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.
- Mapping and implementation of technical solutions to recycle or reclaim resources within the processing plant (e.g., water, detergents, and heat).
- Less food waste due to continuous improvements of shelf life and increased utilization and valorization of side streams – benefitting from Danish strongholds within the ingredient and processing industry.
- Improving branding possibilities and transparency of the food chains towards consumers, customers, and present and future employees as well, leading to increased competitiveness, job satisfaction and job retention.
- A wide range of sustainable, food products and ingredients with a low carbon footprint meeting the different consumer/customer demands regarding origin of raw material, taste, nutritional value, shelf life, food safety, and overall attractiveness.
- Reducing the regulation barriers related to implementation of new solutions in the food processing industry. Relevant regulation aspects include food safety and approval of alternative technologies (chemistry, allergy, microbiology), big data and data science versus GPDR, nutrition, energy network, and water management.

BEST ESTIMATE OF SPECIFIC IMPACT ON THE STRATEGIC GOALS AND SOCIETY
The effort in terms of climate and resource efficient food processing will contribute substantially to:

The overarching goals for climate
- 70% reduction of carbon emissions by 2030 compared with 1990 levels.
- Carbon neutrality no later than 2050.

Strategic goals for waste, water, and circular economy
Denmark to become world leading society within circular economy by 2030.
- Energy- and- climate neutral water and waste handling sector in 2030.

Please also refer to the sections on “Objective and goals” and “Concrete goals”.

BUSINESS POTENTIAL AND ADDED VALUE IN DENMARK AND INTERNATIONALLY
The food sector has already initiated the journey towards becoming more climate and resource efficient. What may initially have been part of securing the license to operate, the industry players now see the potential of using the green transformation to further branding of Danish food products, processes, and services while at the same time doing their part securing the existence of a healthy and sustainable Earth.

The added value for companies and society will be:
- Reducing the environmental footprint of the products and processes, which may position the Danish food industry as first movers when it comes to climate neutral food products and ingredients, food processing technologies, and services.
- Branding – towards consumers, customers, and towards current and future employees (stewards in the green transition).
- Resource optimization and increased product yields will lead to better earnings and consequently create or retain jobs in Denmark, thereby contributing with tax income required to retain the public sector.
- New technologies, and other market opportunities for the Danish producers of technologies in Denmark and abroad.
- A portfolio of products with a low carbon footprint that will provide the consumers/customers with sustainable, healthy, affordable foods that are also culturally acceptable – specifically tailored for the individual needs of the different global consumers/customers.
- Establishment of start-up companies that may help develop solutions with low GHG emissions that e.g., the current technology providers are unable to provide.
- Production of plant-based ingredients with high technological functionality based on gentle processes is expected to have a huge impact on the Danish economy, since there is a large worldwide demand. In this context, ingredients based on Nordic crops are of special interest, as they are perceived as healthy and sustainable.
- Processing equipment, microbial cultures, analytical equipment, robotics, etc. will be developed – all having a large export potential, further strengthening the Danish exports and economy. For example, Chr. Hansen expects that the market of fermented plant-based foods will contribute positively to the revenue of the company in the order of +100 m DKK over the coming 5-year period. FOSS conservatively estimates a potential annual revenue of >50 m DKK by 2025 from instrument sales and digital services to the plant-based alternative industry. KMC expects that protein-based ingredients

will increase the turnover for specialized ingredients by 10 % over the next decade. These are just a few of the positive business cases and expectations for the future.

- Lifelong learning for the employees and securing state-of-the-art research-based training of university students (making them attractive in a competitive, international job market).

Inflection points and milestones

INFLECTION POINTS
The TRL levels for the food industry vary from one sector to another and depend on the research topic at hand. For instance, the meat industry is well-advanced when it comes to automation, whereas automation is still in its infancy when it comes to plant-based products. On an average, the TRL level is expected to advance from 2 in 2021 to 4 in 2025, 6 in 2030 and 8-9 by 2050 when reviewing climate and resource-efficient food processing.

MILESTONES
The following lists potential milestones. However, this will obviously be dependent on the resources used to develop the area.

By 2025

- Proof of concept of sustainable and cost-effective technologies for extraction of high-quality components from animal side streams.
- At least two proofs of concept in relation to new technologies have been implemented.
- Analytical tools for implementing digital strategies and digital sensor systems coupled with robotics.
- Tools to map resource efficiency.

By 2030

- Fully tested models of electrification.
- Replacement of current technologies with at least four new proofs of concept implemented.
- Proof of concept of gentle extraction of proteins from a variety of plants and side streams (one being rapeseed for human consumption).
- Introduction of new sensor technologies to the entire food production sector.
- Widespread use of quality by design using appropriate sensor technologies in Danish plants.
- Proof of concept of sustainable approaches and equipment for separation, purification, and concentration of plant proteins.
- Fermentation and/or enzymatic approaches to improve functionality, taste, and nutritional value.
- Water efficiency initiatives implemented.

By 2050

- Replacement of current technologies with precision food processing technologies.
- Fully tested models of electrification.
- Quality by design using appropriate sensor technologies in Danish plants.
- Integrated tools to monitor resource efficiencies in food processing.

Risk management and alternatives

The following topics have been identified as risks in terms of reaching the goals. Risk mitigation is provided for each topic:

- Regulatory approval of novel technologies and novel raw materials (e.g., fractions derived from side streams). Subprojects will be designed to provide the necessary documentation for the competent authority, and the authorities will be partners, thereby ensuring that solutions are only developed that stand a fair chance of being approved.
- Lack of scalability – early-stage and continuous involvement of industry supply chain helps ensure that upscaling is possible.
- Lack of consumer acceptance – consumer aspects need to be in focus all the time. Lack of buy in from the consumers/customers is a no-go.
- The developed technologies render unsafe products – food safety and quality issues are monitored for all solutions, so this should not be an issue.
- Insufficient human resources to take on the task of converting the food processing sector. A real threat as human resources and the right competences are limiting factors. Focus must be on solving the issues with the highest impact.
- Furthermore, the development of a competitive and efficient power grid and biogas grid is critical for a “greener” selection of production processes. We have no mitigation plan for this. It must remain a political top priority.

Relation to other tracks

As stated earlier, food processing is part of both vertical and circular value chains. As such it links to all tracks dealt with in this roadmap. GHG emission accounting systems, a data-driven agri-food system, regulation, and incentives from farm to consumer.

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 table 11.

TABLE 11 Common activities in the first year of all partnerships.

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.

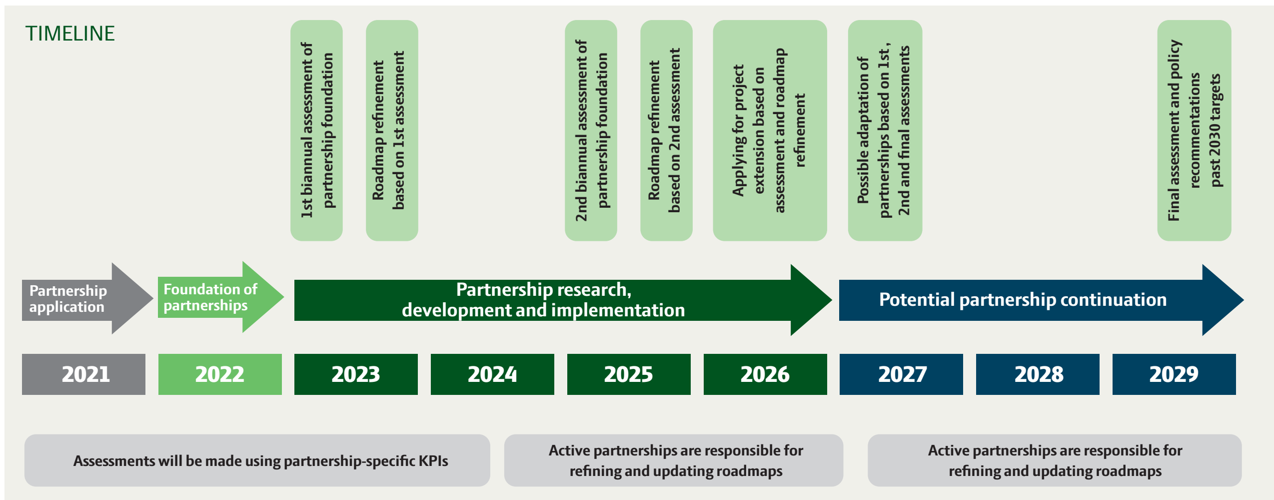
Milestones, timeline and success criteria

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 sustainable food and agriculture with a low GHG emission 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.

FIGURE 3 Partnership progress and development.



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 simultaneously 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 prioritization to the boards.

RELATIONS TO OTHER ROADMAPS AND MISSIONS
Achieving an griculture and food production, which also meet the environmental and climate goals, is one of four research and development (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 neutral 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 bio-oil 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, both established and start-ups.

The climate challenge requires internationally concerted actions governed by the United Nations (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 neutral 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 greenhouse gases was initiated in 2009 at the COP 15 in Copenhagen and brought more than 3,000 experts from 60 countries and partner organizations (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 m EUR funding, under the umbrella of the Horizon 2020 Research, Technology Development and Innovation (RTDI) framework programme. In the next Horizon Europe programme, climate related RTDI is even more prioritized, 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 behavioral 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 b DKK annually, employs 190,000 people and accounted for 170 b 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 national goals partly because the Danish market for green solutions is limited and partly because many of them are hard to commercialize (e.g., many biodiversity goals).

Technology and innovation funding of 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 in three new plant protein processing and production plants. 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 (Copenhagen Economics, 2020. Finanssektorens klimapartnerskab baggrundsrapport). 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

Sustainable agriculture and food systems continue to play a key role for Danish farmers and Danish industries in terms of national employment and international competitiveness. To keep the leading role, there is a need of approx. 12.5 b DKK annually in private and public investments to reach the 2030 goals. The annual estimated need for funding and investment in research, innovation and upscaling solutions (2021-2030) is estimated to 1,500 m DKK for Land Use change, 4,000 m DKK to mitigate GHG from the animal-based food production, 3,000 m DKK to develop plant-based food production systems and 4,000 m DKK for developing biotech including alternative proteins.

The estimations include already existing investments in research, innovation and technology development at both public and private level. To the existing funding are added expected increases in research and technology investments. Existing investments in TRL 1-4 mainly include public and private foundations. Whereas investments in TRL 5-9 include public and private foundations as well as private investments and investments in processing facilities. It is expected that investment in processing facilities will increase towards 2030 and be lower at the beginning of the period.

LAND USE
It estimated that there is a need to increase TRL 1-4 basic research by 150 m DKK from public foundations and 300 m DKK from private foundations annually. The research and innovation at TRL 5-9 is estimated to be 150 m DKK from public foundations and 600 m DKK from private foundations annually. Further private investments are estimated to amount to 300 m DKK annually. No processing facility investments are expected in this area and public "land purchase" is not included in the estimation.

ANIMAL-BASED FOOD PRODUCTION
It estimated that there is a need to increase TRL 1-4 basic research by 200 m DKK from public foundations and 200 m DKK from private foundations annually. The research and innovation at TRL 5-9 is estimated to be 400 m DKK and 600 m DKK from private foundations annually. Further private investments are estimated to amount to 1,200 m DKK annually. The area includes significant investments in new technologies amounting to approx. 1,400 m DKK annually.

PLANT-BASED FOOD PRODUCTION
The need for TRL 1-4 basic research is estimated to 300 m DKK from public foundations and 300 m DKK from private foundations annually. The TRL 5-9 research and innovation is estimated to be 300 m DKK and 300 m DKK from private foundations annually. Further private investments are estimated to amount to 900 m DKK annually. As the area includes new technology and new production methods extensive processing facility investments are expected amounting to 900 m DKK annually.

BIOTECH AND ALTERNATIVE PROTEINS
The need for TRL 1-4 basic research is estimated to 400 m DKK from public foundations and 400 m DKK from private foundations annually. The TRL 5-9 research and innovation is estimated to be 400 m DKK. Investments from private foundations at TRL 5-9 are not foreseen for this area. Further private investments are estimated to amount to 1,200 m DKK annually. Many technologies are still in the early stages and there is a need for extensive investments in processing facilities amounting to approx. 1,200 m DKK annually.

EXAMPLES OF FOUNDATIONS AND INVESTORS
TRL 1-4 public foundations: Danmarks Grundforskningsfond, Det Frie Forskningsråde, ERC etc.
TRL 1-4 private foundations: Novo Nordisk Fonden, Villum Fondene, Carlsbergfondet, B&M Gates Foundation etc.
TRL 5-9 public foundations: Innovationsfonden, GUDP, MUDP, Horizon Europe etc.
TRL 5-9 private foundations: Landbrugets afgiftsfonde, mindre fonde etc.
TRL 5-9 private investments: Company research, Vækstfonden, Danmarks Grønne Investeringsfond and private technology investments incl. in agriculture.

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 b 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 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 commercialization 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 developing 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 specialized 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. Organization 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 such 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 crosscutting 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 ca. 300 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 organizations have been informed, involved, and consulted throughout the process to make sure that the roadmap truly represents the interests of all stakeholders.

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