atf animal task force
A European Public-Private Partnership

A Strategic Research and Innovation Agenda for a sustainable livestock sector in Europe

Challenges, ways of progress and suggested priorities for research for Horizon Europe to enhance innovation and sustainability in the livestock production sector of Europe's food supply chains

Fourth White Paper of the Animal Task Force

August 2024

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This paper is a consulted paper prepared by ATF members and engaged partners.[1]

About the Animal Task Force (ATF)

ATF is a European Public-Private Partnership and a leading body of expertise linking European industry and research providers for developing innovation in the livestock sector.

We work together to identify actions that are needed to foster knowledge development and innovation for a sustainable and competitive livestock sector in Europe.

[1] For details about Animal Task Force (ATF) and concertation organised during the last 2 years, see appendix 1

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Abbreviations and networks

AH&W: Animal health & welfare
AMR: Antimicrobial Resistance
ASF: Animal-Source Food
Cofund ERA-NET SusAn Sustainable Animal Production
C/N ratio: carbon/nitrogen ratio
CH_4: methane
CO_2: Carbon dioxide
COP 21: 2015 UN Climate Change Conference in Paris
CSA: Coordination and Support Action
DG AGRI: Directorate-General for Agriculture and Rural Development (European Commission)
DG CLIMA: Directorate-General for Climate Action (European Commission)
DG CONNECT: Directorate-General for Communication Networks, Content and Technology (European Commission)
DG ENVI: Directorate-General for Environment (European Commission)
DG RTD: Directorate-General for Research and Innovation (European Commission)
DG SANTE: Directorate-General for Health and Food Safety (European Commission)
EC DGs: European Commission Directorates Generals
ETP Plants for the Future European Technology Platform
FoodForLife ETP: Food for Life European Technology Platform
EATiP ETP: European Aquaculture Technology and Innovation Platform
ERA-NET: European Research Area Network
ESFRI: European Strategy Forum on Research Infrastructures
EU: European Union
EUP: European Partnership
FACCE-JPI: Joint Programming Initiative on Agriculture, Food Security and Climate Change
FAO: Food and Agriculture Organization of the United Nations
G2P: Genome to phenotype
GASL: Global Agenda for Sustainable Livestock
GHG: Greenhouse Gases
GMO: Genetically modified organism
GRA GHG: Global Research Alliance on agricultural greenhouse gases
HDHL JPI: Healthy Diet for Healthy Life Joint Programming Initiative
HE: HorizonEurope - EU's research and innovation funding programme from 2021-2027
H2020: EU's research and innovation funding programme from 2014-2020
ICT: Information and Communication Technologies
IoT: Internet of Things
LCA: Life Cycle Assessment
MEP: Member of the European Parliament
mRNAs: colostrum messenger ribonucleic acids
NGO: Non-governmental organisation

NH_3: Amonia
N_2O: nitrous oxide
N/P ratio: nitrogen (N) / phosphorus (P)
OH^-: hydroxide
PCR: polymerase chain reaction
pH: potential of hydrogen
PREZODE: Preventing ZOonotic Disease Emergence
PU: Production Unit
R&I: Research & Innovation
RI: Research Infrastructures
RRI: Responsible Research and Innovation
SCAR: Standing Committee on Agricultural Research
SCAR CWG-SAP – SCAR Collaborative Working Group on Sustainable Animal Production
SCAR Strategic Working Group AKIS - SCAR Agriculture Knowledge and Innovation Systems
SD: Sustainability Domains
SRIA: Strategic Research and Innovation Agenda
TP Organics: European Technology Platform for Organic food and farming
UN SDGs: Sustainable Development Goals of the United Nations
WHO: World Health Organization

Introduction

This Strategic Research and Innovation Agenda (SRIA) provides suggested priorities for R&I and their overall expected impacts within Horizon Europe, with the aim of moving towards a resource efficient, sustainable, competitive and safe livestock production sector in Europe fostering more sustainable food systems. A first SRIA for Horizon Europe[2] was published in 2021. The SRIA describes priorities derived largely from the Vision Paper[3] while considering recent and on-going research projects and new instruments promoted by the Commission (missions, partnerships).

We strongly believe that the objectives of the Green Deal provide the right direction for sustainability of food systems, but the recent crises (Covid 19, Ukrainian war) also point out the food security and strategic autonomy issues. The challenge is to progress towards the right balance between food security and environmental and societal demands, to reinforce the central role of animal farming for the provision of high-quality food and for the development of sustainable agriculture giving the huge diversity of European regions. Research must contribute to designing strong policy with a high level of environmental and climate ambition as well as designing productive systems with lower impacts and giving a place to systems with lower productivity that could provide a panel of ecosystem services. The objective is to provide knowledge and solutions that promote responsible livestock as it was defined in the Vision Paper[4]. To fulfil its roles, maximise synergies and avoid trade-offs between the priorities, livestock systems should evolve to provide a range of goods and services, rather than be guided by the single goal of commodity production. Faced with the importance of the changes to be made, the development of innovations must integrate biotechnical and social sciences. Consequently, the socio-economic aspects are more developed than in the previous SRIA.

The scope of the document is European terrestrial livestock, including herbivores (ruminants, horses, rabbits) and monogastrics (pigs, poultry). Blue Growth and aquaculture, addressed by the European Aquaculture Technology and Innovation Platform (EATiP) are not considered although we fully acknowledge that interrelations between green and blue economies should be carefully considered to achieve sustainable European food systems. The document considers the diversity of farming systems as we need to improve the sustainability of the current European intensive systems, as well as promoting low input systems including organic farming. All these systems have their own strengths which can be further enhanced and limitations which should be reduced to fit the objectives while increasing the resilience of the whole sector. Insect breeding and production for feed is addressed in the context of the circular economy.

This document was developed by the ATF Presidency and Secretariat in consultation with ATF members in 2022 and 2023. Some topics were developed in collaboration with European Technology Platforms (ETPs) notably, Plants for the Future[5], TP Organics, Food for Life. This document was also inspired

[2] http://animaltaskforce.eu/Portals/0/ATF/ATF_Strategic_Research_and_Innovation_Agenda_April2021.pdf

[3] http://animaltaskforce.eu/Portals/0/ATF/2024/ATF_Vision%20Paper_2024.pdf

[4] By "responsible livestock" we mean livestock farming contributing to circular and resilient agriculture ensuring food security while keeping resources use within the planetary boundaries, promoting the provision of ecosystem services and biodiversity, reducing the negative net environmental impact associated with that production, ensuring high health and welfare standards for livestock, providing better human health and well-being, contributing to social and economic sustainability through vibrant rural livelihoods, enhancing the resilience of the sector by increasing its ability to withstand physical and financial shocks.

[5] ATF-Plants for the Future Position Paper, September 2019: http://animaltaskforce.eu/Portals/0/ATF/Downloads/ATF_Plant_ETP_joint-paper_Sept2019.pdf

by the strategic approach to EU agricultural Research & innovation (European Commission), ATF participation in the FACCE-JPI[6] stakeholder and HDHL-JPI[7] events, SCAR groups (Sustainable Animal Production, Animal Health and Welfare, Bioeconomy, Agroecology, Food Systems, Foresight Task Force), exchanges of views with EC DGs (namely DG AGRI, DG RTD, DG ENVI, DG CLIMA, DG CONNECT, DG SANTE), European Parliament members and FAO representatives. A large range of European and national state stakeholders were also consulted (see table 1) from industry, farmers organisations, branch or value chain organisations, NGOs, think tanks, international organisations, etc.

Suggested priorities

We suggest focusing on themes where the approach at the European level brings a real added value compared to national approaches. This concerns subjects relating to issues of common interest (such as environment or animal health and welfare) or topics related to analytical research situated at a pre-competitive level that the stakeholders/countries can then use to develop their own strategies (such as understanding the functioning of animal-related microbial ecosystems). This also concerns research requiring scientific expertise and/or a diversity of local conditions or research infrastructures that can only be brought together by the mobilisation of several countries (such as resilience of livestock systems, research on animal biology) in order to be able to implement the full benefit of a G2P (Genome to Phenotype) approach.

Four sustainability domains and a cross-cutting issue

We summarised the main challenges facing the European livestock sector into four sustainability domains (SD) (*Figure 1*) consistent with the Global Forum on Agriculture[8] and in line with our previous Strategic Research and Innovation Agenda. These are key objectives for a just and safe transition of European livestock food and farming systems that merit support from European research and innovation funding. The SRIA also proposes a cross-cutting issue on animals because livestock is a keystone of the systems and is at the crossroads of the four SD.

&. ATF-Plants for the Future Policy Brief, May 2020: http://animaltaskforce.eu/Portals/0/ATF/Downloads/ATF-PlantETP_Policy_brief_April2020.pdf

[6] https://www.faccejpi.net/en/faccejpi.htm
[7] https://www.healthydietforhealthylife.eu/
[8] https://www.gffa-berlin.de/en/home/

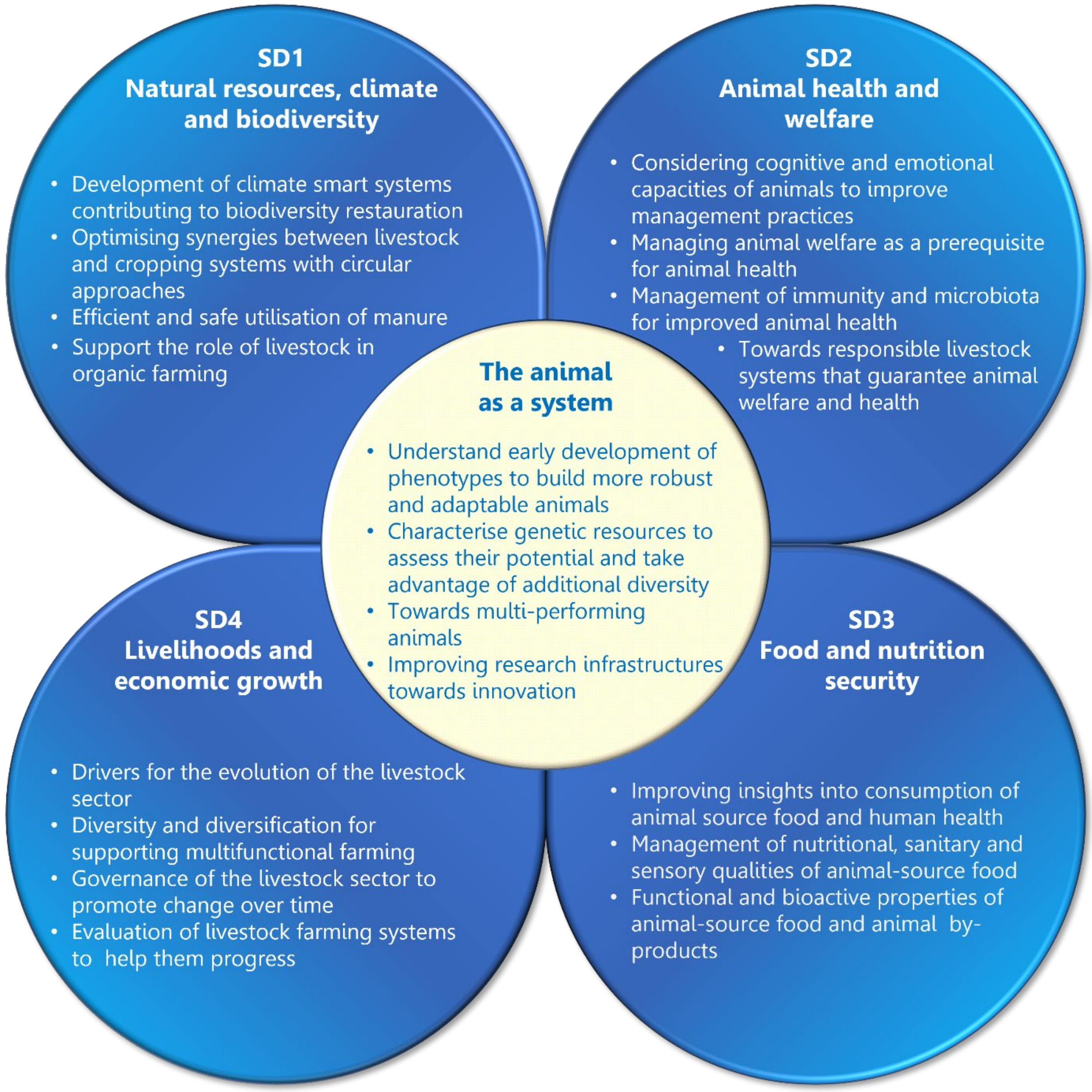

Figure 1. Four sustainability domains and one cross-cutting issue to improve European livestock farming systems

1. **Climate, biodiversity and natural resources (SD1)**. The objectives are to maximise the potential of the livestock sector to mitigate GHG emissions and sequester soil carbon, maximise resource use efficiency and quality and minimise use of non-renewable components, nutrient losses to water bodies and air while minimising direct competition for arable resources between livestock and humans, exploiting manure nutrient content and other organic waste from the agri-food sector. Another ambition is to contribute to the restoration of biodiversity, fostering high natural value farmlands and domestic biodiversity in different ecological and economic contexts. This includes enhancing the roles of livestock in the emergence of circular approaches and finding new interplays with crops to improve livestock feed/nutrient efficiency, reduce GHG emissions and find ways of adaptation to climate change.

2. **Animal health and welfare (SD2).** The objectives are to design and implement integrated management of animal health and

welfare to engage further on a prudent and responsible use of veterinary medication, to reduce economic loss and animal suffering related to the production diseases and to prevent and build resilience to pandemics. Respecting animal welfare and integrity will comprise a reduction of mutilation practices and the development of practices at farm, transport and slaughter, favourable to the expression of positive welfare, including the relationship between physical and mental health. The research topic of the choice given to the animals and the possibility of controlling its environment can also be extended to other parameters. Combined with ethologic progress, it will deliver benefits for animal health and welfare and environment (one health approach). The challenge is to formulate global one health approaches to combat animal disease emergence.

3. **Food and nutrition security (SD3)**. The objective is to understand how and to what extent livestock systems and animal-based food will contribute to the emergence of sustainable and healthy food systems taking advantage of the multi-functionality of livestock, nutritional density and intrinsic quality of animal-based food. The SD is developed in a context of controversies concerning the role and place of products of animal origin in the diet, and at the same time a European population which is getting older for which nutrient density of ASF is becoming more and more important.

4. **Livelihoods and economic growth (SD4).** The objective is to contribute to improved livelihoods and economic sustainability by creating attractive employment opportunities in economically viable livestock systems and to reinforce the roles of livestock farming in the society. This will require the design of public policies and regulations to guide and support efforts for transitions, renewed organisation and coordination between stakeholders to change the socio-technical system required for the development of a sustainable circular economy. Increasing resilience of farming systems to face climate, health and economic hazards is another important issue. The accurate and holistic evaluation of the multi-performance of farming systems, notably agroecological farming systems, is another challenge to better define the political agenda towards sustainability of European farming systems considering both local (territories) and global (planet) challenges.

5. **Cross-cutting issue – The animal as a system (SD5).** New challenges and new technologies (with the use of high throughput technologies; opportunities are increasing) renew the paradigm of research at the animal level and would make it possible to improve the accuracy of animal breeding and managing for optimising animal performances for resilient, diverse and low carbon footprint production systems. The search for efficient animals capable of coping with variable production conditions without compromising product quality implies a new approach in animal biology. In accordance with agroecological principles, this requires refinement of genetic variability and physiological regulations mechanisms by taking into account genomic variation in livestock, microbiomes and pathogens, as well as the epigenetics and to move from a short-term vision of the animal to the integration of time-windows on the same individual and across generations. This will make it possible to understand the animal's capacity to orchestrate various priorities, manage perturbation, resource allocations between organs, production and basal functions in relation to resilience and efficiency over the course of life, and finally to renew breeding goals and trait expressions considering genotype-environment interactions in predicting the reproductive values of individuals for long-term changing climate. This SD renews the interest of research on animal physiology and it is not only based on genetics.

All sustainability domains are interconnected and research must consider the strategies most suited to developing win-win approaches allowing progress in different areas of sustainability at the same time or at least solving a problem while limiting trade-offs with other aspects of performance of the livestock systems. Faced with the importance of the changes to be made, the development of innovations must integrate biotechnical and social sciences. The socio-economic aspects as well as co-construction of solutions with stakeholders are more developed than in the previous SRIA. Research must integrate different levels from the animal and the herd to land use and to the society and for each level acting on the 3 pathways of progress (efficiency, circularity, diversity) - as presented in the Vision Paper - allows us to move in this direction.

Three pathways of progress

The development of more responsible livestock systems requires the deployment of new and better knowledge, responsible use of new technology and know-how, new understanding of social interactions within value chains, new business models with new value-sharing principles, as well as supportive policies and legislation. We propose a smart and coordinated approach based on (i) innovations and science-based solutions and (ii) transition to more sustainable systems and value chains supported by fair, inclusive and innovative governance. This approach mobilises three pathways of progress which can be applied in synergy in the different Sustainability Domains.

1. **Efficiency**: Improving biological efficiency will lead to reductions in (scarce) resource use and more globally in the physical flows into and out of the production system, and the associated negative impacts that arise from these flows. It is also a key element for farm profitability. This is the "sustainable intensification" approach. Efficiency can be considered at the appropriate level of a specific Production Unit (PU) that can be at animal, herd, field or at an even larger level such as the farming system considering internal recycling within the PU.

2. **Circularity:** Beyond efficiency of a given PU, promoting exchanges between PU can lead to new opportunities. This can be considered at different scales both within a farm or between neighbouring farms, or even between regions. Circularity concerns the reuse of various resources (e.g. plant biomass, manures) to avoid wastes, and regeneration of ecosystems by closing natural cycles (nutrients, organic matter). Livestock farming plays a crucial role in circularity as animals are natural recyclers and a significant part of nutrients and biomass flows in agriculture are related to livestock farming.

3. **Diversity:** Beyond the diversity of regional and local contexts that required tailored solutions, diversity/diversification is a means for increasing the performances of food systems, including their resilience (e.g. biodiversity preservation). Diversity must be considered at the different levels of organisation, including animal (and plant) genetic diversity farming systems, animal products, but also diversity of landscape. Diversity/diversification is a means of action for increasing functional complementarities between PU (circular approach) and relying on more nature-based solutions with additional benefits towards a more efficient use of natural resources, low carbon systems, reduced use of antimicrobials (and pesticides when considering the plant sector), vulnerability to animal diseases, adaptation to climate change, and increased circularity between PU.

Coordination and complementarity with European initiatives

The Commission has acquired new research programmatic initiatives (i.e. missions, partnerships) to trigger a real change in paradigm beyond the previous more fragmented initiatives (FACCE JPI, ERA-NETS, etc.). Some of these initiatives directly concern livestock, notably animal health issues (i.e. PAHW partnership, international initiative PREZODE) or livestock is *a priori* embedded in the theme of the initiative. We define our priorities in this new context with the objective to avoid duplication, to find synergies between our SD and EUPs dedicated to the same domain, promote the contribution of the livestock sector to the different partnerships and to build some bridges between the partnerships when considering topics related to the livestock sector. The holistic approaches we promote are complementary to the more targeted and smaller projects that will be funded by the EUPs. This is a first attempt of a link that could be made because the SRIA of EUPs will be revised and updated regularly.

- Agroecology Living Lab partnership[9]: SD1 (and to some extent SD3, SD4 and SD5) partly rely on the priorities of this partnership when considering coupling animals and plants, diversity (genetic, farming systems) and food systems. Our proposals will reinforce the contribution of the livestock sector in this partnership. We strongly support the living Lab, multi-actor and real-live testing approaches, they are very relevant for our SD and for the cross-cutting issue. The reconnection between animals and plants which is one of our priorities in SD1 is at the heart of agroecology approach. Similarly, in SD2, management of immunity and microbiota for improved animal health is an agroecological approach dedicated to animal health but animal management does not yet appear in the partnerships.

- The Partnerships "Animal Health and Welfare"[10] (AH&W) and PREZODE initiative[11] aim to understand specific health questions and particularly they aim to understand the risks of emergence of zoonosis, to prevent emergence, to better control animal infectious diseases and therapeutics, to develop curative approaches and risk assessment and protect public health as well as animal welfare (for AH&W partnership). We fully support these priorities. The SD2 puts more emphasis on the link between animal welfare and animal health as part of the One Welfare concept and on the prevention side in relation to herd management in line with other SD and to the interplay between animal welfare, animal health and environmental issues, notably GHG emissions which is less central in these initiatives.

- The partnership "Agriculture of Data"[12] is central for our SRIA. For all SD and notably SD1 and SD2, sensors, robotics, Internet of Things (IoT), artificial intelligence and data science provide innovative tools and concepts for livestock management through the continuous, automated and real-time monitoring of a growing number of parameters on the animal and its environment. Interactions between animal and automates are another dimension. It raises additional challenges to be addressed: how the animals learn using automates (self-feeders, etc.) but also conversely, how this automation can allow the animal to adjust its own environment for its health and welfare. The challenge of data integration and interpretation to promote efficiency and circularity in livestock farming is also essential.

- The Partnerships "Water4All"[13] (water security), "Safe and Sustainable Food System"[14] (transition towards sustainable food systems), and the Missions "Adaptation to Climate Change"[15] (adaptation to climate change in European regions) and "A soil Deal for Europe"[16] (transition towards more healthy soils) embedded livestock for a (small) part of their activities. SD1, SD3 and SD4 provide R&I ideas which can fertilise these initiatives while affirming the place of livestock farming in their R&I projects. In turn, these initiatives will

[9] https://research-and-innovation.ec.europa.eu/research-area/agriculture-forestry-and-rural-areas/ecological-approaches-and-organic-farming/partnership-agroecology_en
[10] https://research-and-innovation.ec.europa.eu/system/files/2022-04/ec_rtd_he-partnership-pahw.pdf
[11] https://prezode.org/
[12] https://research-and-innovation.ec.europa.eu/document/download/a1fccc86-af53-43d4-94d2-79c54a353d0e_en?filename=ec_rtd_he-partnership-agriculture-data.pdf
[13] https://water4all-partnership.eu/
[14] https://research-and-innovation.ec.europa.eu/document/download/a35be177-7024-4849-843f-c8bfa7892712_en?filename=ec_rtd_he-partnership-sustainable-food-systems-april_2022.pdf
[15] https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/adaptation-climate-change_en
[16] https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/soil-health-and-food_en

provide enriched context for livestock research and provide place-based approaches for livestock research for some of them.

Our priorities also consider past and on-going funded projects (H2020, HE) that are closely related to suggested research and innovation priorities but do not fully address the issues mentioned. We have highlighted some on-going collaborative projects supported by H2020 & HorizonEurope (see appendix 2).

Open innovation

Many proposed areas of research will require collaboration between all key actors including public and private actors to enhance cross sector cooperation and collaboration and to ensure that innovations (technological and organisational) truly correspond to a shared need and are disseminated as quickly as possible. Furthermore, as the development of solutions based on the principles of agroecology (and nature-based solutions) makes the systems more dependent on the local context, the continuous development of Living labs must be encouraged to address the wide geographical and regional specificities in the EU through place-based approaches.

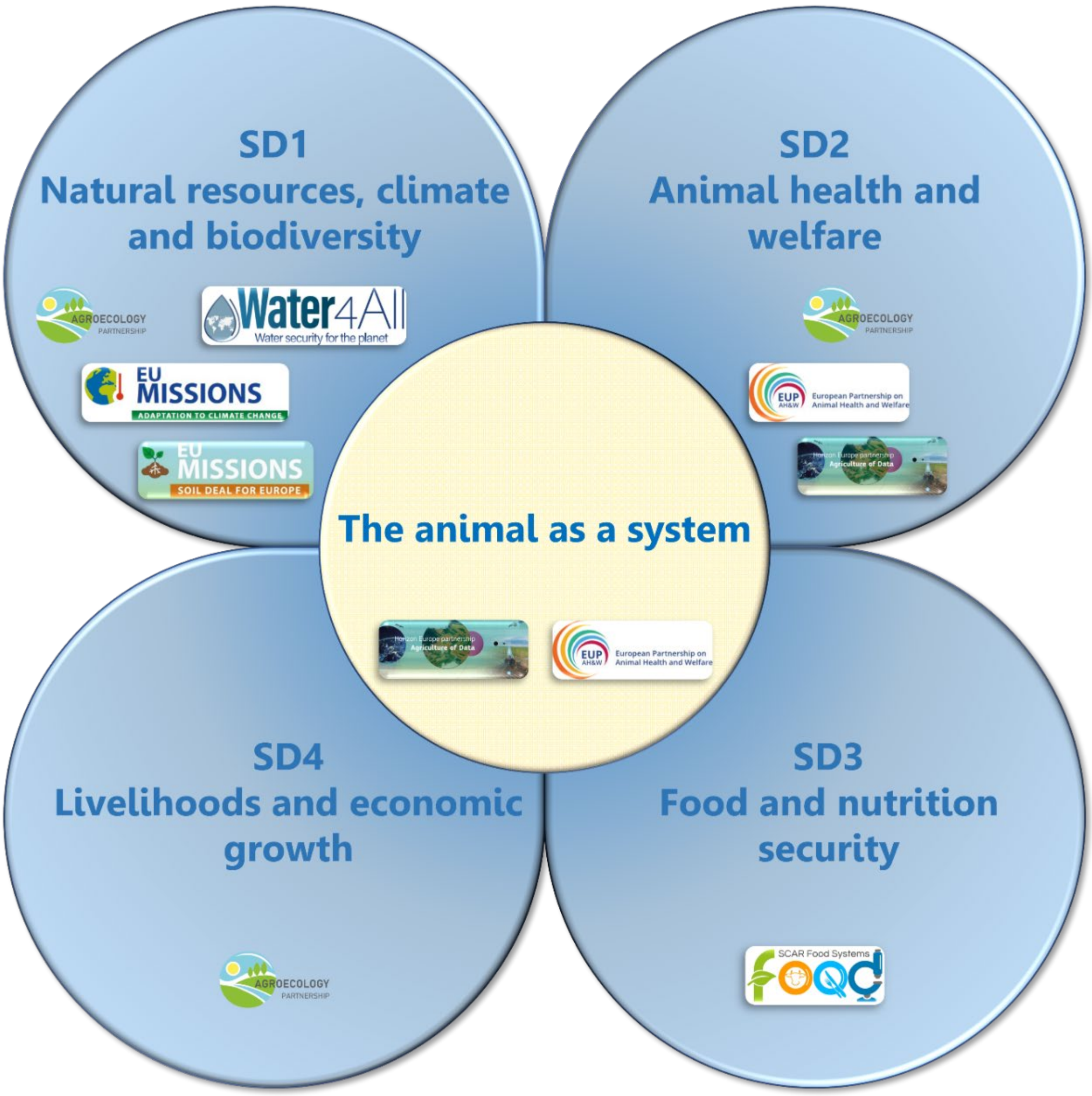

Figure 2. Illustration of complementarity between the SRIA and other EU initiatives

Topics list[17]

Suggested priorities are listed below for R&I that may support a transition of the livestock agri-food sector towards a greater contribution to sustainable circular agri-food systems, increased efficiency of production, better preservation of the quality of the resources while still producing healthy nutritious food at an affordable price, with fair livelihoods for livestock farmers.

1. Natural resources, climate and biodiversity

1.1. Development of climate smart systems contributing to biodiversity restoration*

1.2. Optimising synergies between livestock and cropping systems with circular approaches*

1.3. Efficient and safe utilisation of manure

1.4. Support the role of livestock in organic farming**

2. Animal health and welfare

2.1. Considering cognitive and emotional capacities of animals to improve management practices

2.2. Managing animal welfare as a prerequisite for animal health

2.3. Management of immunity and microbiota for improved animal health

2.4. Towards responsible livestock systems that guarantee animal welfare and health

3. Food and nutrition security in One Health approach

3.1. Improving insights into consumption of animal-source food and human health***

3.2. Management of nutritional, sanitary and sensory qualities of animal-source food***

3.3. Functional and bioactive properties of animal-source food and animal by-products***

4. Livelihoods and economic growth

4.1. Drivers for the evolution of the livestock sector***

4.2. Diversity and diversification for supporting multifunctional farming

4.3. Governance of the livestock sector to promote change over time

4.4. Evaluation of livestock farming systems to help them progress*/***

5. Cross-cutting issue: The animal as a system

5.1. Understand the early development of phenotypes to build more robust and adaptable animals

5.2. Characterise genetic resources to assess their potential and take advantage of additional diversity

5.3. Towards multi-performing animals

5.4. Improving research infrastructures towards innovation

[17] Topics marked "*" were developed in collaboration with Plants for the Future ETP through a multi-actor approach
See also ATF-Plants for the Future Position Paper, September 2019: http://animaltaskforce.eu/Portals/0/ATF/Downloads/ATF_Plant ETP_joint-paper_Sept2019.pdf
and ATF-Plants for the Future Policy Brief, April 2020: http://animaltaskforce.eu/Portals/0/ATF/Downloads/ATF-PlantETP_Policy_brief_April2020.pdf

Topics marked "**" were developed in collaboration with TP Organics through experts' consultation

Topics marked "***" were developed in collaboration with Food for Life ETP through experts' consultation

1. Natural resources, climate and biodiversity

Challenges

The livestock sector continues to face several challenges. The sector is responsible for about 12% of total GHG emissions (representing 80% of the agricultural GHG) and regional concentration of animal production causes diffuse pollution of air and water altering the functioning of the ecosystems. The sector is also blamed for its consumption of finite resources (land, water and energy) and its role in deforestation is hotly debated. Therefore, the reduction of livestock sector is often proposed as a unique solution. However, an uncontrolled reduction of the sector will have counterproductive effects on economy, food sovereignty and grassland acreage and this too simplistic approach suggests that we need to find ways of reducing the negative impacts.

The challenges go beyond the livestock sector, which is too often considered independently of other agricultural sectors. Matching economic and societal expectations regarding sustainability of our agri-food system, a conversion of the agricultural sector is required that targets nearly every aspect and requires the deployment of technology and new business models with supportive policies and legislation. As a part of the agri-food system, livestock farming is also part of the solution and has a major role to play in a rejuvenated agriculture. To achieve these objectives, livestock systems need to be redesigned to better capitalise on animals' ecological niche as biological up cyclers and providers of organic fertilisers. The search for synergies between crops and livestock is a lever for the development of a thrifty style of agriculture ensuring simultaneously food security and resource sufficiency while supporting the remediation of healthy ecosystems producing recognised services, including soil carbon sequestration and biodiversity restoration. Crop and livestock systems should become more integrated at multiple scales, e.g. on farm with arable and livestock rotations or at a regional/national scale through exchange of by-products and manures/slurries between livestock and arable farms.

All these developments call for science-based innovations based on agroecological and circular approaches. This implies to shift from focusing on the efficiency of a single part of the system towards looking at efficiency of the whole system or territory, therefore seeking the best compromises between tailoring products to customer needs, improving production, using natural and local resources and minimising climate and environmental impacts. The crop-livestock association also raises issues around new economic models, organisational innovations (see SD4) and food safety management. Circularity should be considered at local level (neighbouring farms, small region) and the diversity of situations should be considered to generate generic knowledge and propose locally well-suited solutions. Circularity should also be considered at a larger scale (political region, countries, Europe) to assess the circularity for all the bio components.

R&I priorities

R&I priorities aim to make use of the unique ability of livestock to convert biomass (particularly human inedible) into high quality human edible food and other ancillary products, while closing nutrient cycles and restoring the quality of ecosystems.

1.1. Development of climate smart systems contributing to biodiversity restoration*

The European livestock industry urgently needs to reduce GHG emissions to contribute to ambitious climate change policy commitments and Green Deal priorities. Although much is being done, in particular for methane mitigation[18], there is still some progress to be made towards "net zero" livestock farming using holistic approaches while finding win-win strategies and avoiding trade-offs with other parameters including biodiversity and animal welfare. At the same time, the frequency of hot weather and water scarcity may endanger certain livestock farming systems, notably in Southern countries and more resilient systems must be developed. The development of agro-biodiversity is a factor that can positively contribute to both objectives.

GHG mitigation innovation. The large range of intensity of emissions across farm types indicates that there is a large scope for progress. The major levers of actions are well known[19] but research, fine-tuning, testing, validation, demonstration and monitoring of a wide range of innovations used simultaneously at different scales in different systems must be envisaged (ambitious "system experimentation"). Managing the different levels all together can have additional benefits for protein autonomy, reduction of fossil fuel, soil fertility and biodiversity, especially for evaluating the combined effects of various levers. In this respect, an ambitious "system experimentation" is still lacking.

- Increase livestock efficiency to reduce GHG emissions (notably methane from ruminant). Beyond the classical short-term approach, efficiency must be considered on a long-term basis (at least the entire cycle of production) thus including animal precocity (age at puberty, age at first parturition, shorter length of fattening period), vitality of young animals, longevity of the reproductive females (see SD2). It is necessary to consider efficiency with different metrics, not only the classical ratio between feeds and products (or residual feed intake), but also considering the use of by-products that is likely part of the transfer of efficiency between animal and system. Efficiency should also be considered relative to new production systems (i.e. depending on more diverse feeding resources, using less medicines, facing hotter climate, etc.). For ruminants, the potential of feed additives must be confirmed on a long-term basis (ruminal microflora adaptation?) and they should not compromise other drivers of agroecological transitions and notably the potential of cellulose digestion.

- Develop the use of by-products, crop residues and above all nitrogen fixing plants which are crucial issues not yet well enough quantified and exploited. Legumes can reduce soil emissions, and enteric methane emissions with additional benefits for protein autonomy.

- Reduce emissions from soil fertilisation including smart use of manure aiming at minimising GHG (and ammonia) losses, developing biogas production, replacing mineral fertilisers by organic fertilisers when possible, locally and/or by mineral fertiliser produced from manure thanks to biotechnology.

- Improve soil carbon sequestration to reach "net zero" livestock not only at farm level but also at regional scale considering land use, notably the interplay between livestock and crops (crop diversification, soil cover), changes in spatial distribution of animal production, grassland management, agroforestry and agroecological infrastructures with additional benefits for biodiversity. In addition, the direct effect of grassland on global temperature through its higher albedo than crops and forest should be better evaluated.

- Study the interplay between livestock and notably considering the synergies between ruminants who digest cellulose but produce methane and monogastrics who are more efficient but also more in competition with human food, maximising the interplay between dairy and beef sector for milk and red meat production and considering avenues for improvement achievable in all these production systems.

- Understand the biophysical and market barriers to achieving mitigation requires

[18] https://re-livestock.eu/ and https://pathways-project.com/

[19] https://animalchange.eaap.org/

further research and on-farm demonstration, while evaluating the impact on other performances. Alternative methods to incentivise the use of what are likely to be expensive to mitigate emissions need to be developed.

Adaptation of livestock systems to global warming and water scarcity. If the trend of climate change can be predicted on the medium term, the occurrence of phenomena (lack of water, heat wave) and their duration remain unpredictable. Knowledge must be acquired to develop animals, feeds & forages and management systems that are both more robust on the long term and more resilient on a shorter term. We need to:

- Estimate the vulnerability of water supply to livestock farms, particularly for watering herds and during periods of water pressure, testing the current practices of water use in view of developing prospective scenarios on the availability of the water resource in a context of multi-actor water management at regional level.

- Improve benchmarks to estimate the watering needs of all types of animals, develop diagnostic tools for evaluation of water use efficiency at the scale of an individual animal, herd and farm (livestock water productivity), evaluate individual variability in water use efficiency and behaviour in the face of contrasting competitive conditions for access to water.

- Better understand the mechanisms of animals' adaption to heat waves (or combination of heat and humidity) to propose new genotypes (see cross-cutting issue). Exploitation of the potential of feed additives (antioxidants, methyl donors, minerals, crops and vegetables compounds like polyphenols) that can improve the capacity of the animal to regulate oxidative stress and thus to adapt to heat stress and the use of new technologies to detect the most sensitive animals on which action should be taken are other relevant avenues for improvement.

- Develop more resilient feeding systems that optimise the use of water when it is limited: crops more resistant to water stress (e.g. sorghum, deep roots legumes, multispecies swards, agroforestry) or crops requiring water when it is more available (production of winter crops instead of spring/summer crops). Beyond strategies, a panel of opportunistic practices (e.g. off-season grazing, catch crop fodders, fodders for stocks) should be evaluated.

- Innovate in livestock buildings whose specifications must be established from observation of animal behaviour. Much progress are expected. Adoption requires co-innovation for the development of alternative farming systems in the different climatic zones looking at livestock health and welfare challenges. New technologies and sensors offer the opportunity to the improvement of precision livestock feeding to develop precision livestock watering.

Contribution to biodiversity management and restoration. Livestock farming is often blamed for its contribution to biodiversity losses (deforestation, use of pesticides to produce feed, etc.) but at the same time it could have a very positive contribution (i.e. permanent grassland are hot spots of biodiversity). To evaluate the contribution of livestock farming systems to biodiversity and monitor the best achievable balance between production efficiency, GHG mitigation and biodiversity, we need to:

- Choose, adapt or create scientifically recognised method(s) of biodiversity assessment and develop relevant and understandable biodiversity indicators which are sensitive to changes in agricultural practices and local context (e.g. the impacts of a change in practice may depend on the region) and which consider all types of production systems and farmed species. It is important to consider the farm scale to develop progressive approaches, a more global landscape/ ecosystem scale to promote territorial management, and the ASF product scale for environmental display. A single method will not respond to the three levels of the challenge and the indicators will not necessarily be the same. Management of the tension in terms of objectives and levels of scale is a challenge.

- Consider local and global scales to take into account not only feed produced on the farm and locally but also the effects of purchased feed, notably imported feed. Consider agro/domestic biodiversity and habitat changes that also affect wild biodiversity, and soil biodiversity.

- Promote participatory approaches to define the objectives and manage tensions between the different levels of scale. Which practice should then be favoured in a context where a practice can be favourable for one species but unfavourable for another one? Do we prefer a landscape of forest or grassland, a bocage landscape or uncultivated spaces? This refers to the different values that stakeholders give to biodiversity.

- Develop innovative practices and landscape organisation that favours biodiversity while contributing to reduce net GHG emissions. The role of ruminants and permanent grassland and the balance between GHG emissions, soil carbon sequestration and biodiversity are central.

- Understand how a full integration of biodiversity and environmental schemes in the sourcing of livestock raw materials can deliver value for farmers and consumers.

- Develop new strategies to characterise, multiply and ensure the *in situ* and *ex situ* conservation of genetic resources and promotion of the use of animal genetic resources diversity in commercial breeding programmes for various objectives. A better understanding and mastering of the services to be provided by microbial biodiversity and wild plants on livestock farming should be developed.

1.2. Optimising synergies between livestock and cropping systems with circular approaches*

The advantages of crop diversification are recognised and studied in some European funded projects[20][21], and deal with nutrient cycling, pest control, soil fertility, water flow. These projects did not, or only to a small extent, integrate livestock farming although livestock farming offers additional opportunities, particularly due to its ability to use a diversity of biomass as feed and the production of organic fertilisers. The challenge is to maintain production to meet the food demand and other issues as green energy without the need to expand the agricultural frontier by taking advantage of the diversity of plants (plants species, part of the plants) used by animal species.

Identification and development of mixed crop-livestock systems adapted to local contexts

Crop plants and cropping systems should be adapted so that the plants can be used as a priority for food and secondarily, non-edible parts could be used for feed. Research should identify avenues of progress (breeding, production systems, feed processing and animal diet formulation) to optimise the multiple use of plants for different environmental and economic situations.

- Study the benefits of introduction of dual-purpose crops to produce food and feed simultaneously, locally produced legumes for feed as legume imports disconnect regional agro-ecological cycles. The potential of dual-purpose animal breeds (milk/meat, meat/egg) should also be investigated.

- Study the introduction of grassland (grasses, forage legumes) in crop rotations as a promising protein source either directly for ruminants and after processing for monogastrics. Value of cover crops and crop residues as animal feeds must be evaluated. This requires the development of new or

[20] LEGVALUE: https://www.legumehub.eu/legvalue/

[21] DiverIMPACTS: https://www.diverimpacts.net/index.html

undersown crop species and cultivars of existing crops, (improved) varieties with environmental and nutritional advantages for animal feed.

- The effects of the introduction of trees/agroforestry in grasslands and croplands also need to be elucidated with regards to productivity, feed resource, protection of animals against daily and extreme weather conditions, storage of carbon in soil, regulation of nitrogen fluxes and adaptation to climate change.

- Evaluate sustainability benefits of these new circular feed chains with multicriteria methods as well as the sanitary risks of these novel feeds that may contain anti-nutritional factors or chemical residues or contaminants at low levels (thus implying development of detoxification techniques). Evaluation of ASF (e.g. food safety, nutrition, shelf length and sensory attributes) is also part of the assessment.

New (protein rich) feed sources

The development of circular approaches should make it possible to develop new protein sources for feed which would not be in competition with human food. The priorities are:

- Evaluate the production of earthworms in particular for poultry farming, as a source of natural protein making use of organic waste and compost with a low need of energy. The potential use of algae and micro-algae as lipid supplements rich in poly-unsaturated fatty acids with benefits for the nutritional quality of animal products and as biocontrol products for animal health should be further explored.

- Further explore a diversity of biomass valuable for feed use such as by-products from agro-food industries or green chemistry, former foodstuffs, other biomass streams as crop residues in support to circularity. This exploration has to include global environmental impact of this production. The issues of daily availability must be addressed and can raise research questions about the temporal availability of these feeds and chrononutrition for the animals (i.e. feeding animals with a different diet depending on the availability of the coproducts in the industrial workflow). Detoxification of feed from anti-nutritional compounds, contaminants and pathogens is another important area since some of these novel feeds may contain anti-nutritional factors (i.e. mycotoxins) or chemical residues or contaminants.

Upgrading the ability of livestock to utilise a diverse range of inedible biomass

We need animals that can thrive on European feedstuff, European legumes and non-edible crop parts and that perform well with less traditional feed which are often of a lower quality. In addition, new feed resources will often be very variable in location, time and quality, which raises specific questions for livestock production.

- Explore physiological and genetic determinants of animal feed efficiency (after Feed-a-Gene[22]) using resources of medium to low quality and more diversified, which could exacerbate inter-individual differences and interaction between various nutrients.

- It will also require better knowledge of animal adaptation and *ex-ante* prediction of animal performance in response to a diet. The optimisation of use of diverse feed resources requires precision feeding techniques to assist farmers and novel information systems to assess availability and price, considering the variability of available livestock competitions of use (feed, energy, green fertiliser) and local contexts (agronomy, economic, transport, organisation between farms), feed safety.

- Processing of green biomass and new protein-rich sources has potential to improve their nutritional value and to isolate plant secondary compounds having beneficial effects on animal health.

A full achievement of circularity requires precompetitive research on plant genetics,

[22] Feed-a-Gene https://www.feed-a-gene.eu/

notably legumes but this is not part of this SRIA. Precompetitive research on livestock breeding with due consideration on efficiency and resilience is described in part 5.

Addressing the wide geographical and regional specificities for the reconnection between livestock and crop farming

The development of circular solutions based on the principles of agroecology must be considered according to local conditions to promote the solutions that are most adapted locally. In this context, the development of place-based approaches as proposed by the Agroecology Living Lab partnerships are very relevant. We need to:

- Promote and analyse the environmental and economic impact of various local initiatives aimed at (re)connecting crops and livestock. This concerns, for example, sheep or poultry grazing in cereal plains and orchards, the association of cereal and livestock producers for the reason of more diverse crop rotations or fertilisation practices and the development of coupled markets, the use of animals as agents of prophylaxis and biocontrol in specialised crops (vineyard, arboriculture, market gardening), etc.

- Identify factors of success and coordination challenges arising from the combination between individual initiatives and collective approaches.

- Provide stakeholders in the territories and food sectors with objective and solid elements of evaluation of better integration of livestock farming with plant production in the territories and also to specify how this integration can be a driver of the agroecological transition of the territory and a major factor in sustainability. To date, the results of current and future initiatives are currently dispersed, which does not allow their evaluation or dissemination.

Supporting efficient organisation of stakeholders and innovative public policies

The objective is to change the socio-technical system while ensuring business continuity to support closer coupling of feed production and use of organic fertilisers. Priorities are:

- Explore and demonstrate new business models to integrate innovation into local circularity approaches.

- Provide information for the design of new public policies, to develop specific measures to "protect innovation niches" during the experimental period, to define the most appropriate policy tools towards a transition (payment for environmental services, other incentives, taxes and regulations), assess the consequences of new policies in terms of production, income, trade, health and environmental services.

- Develop optimal traceability methods to increase transparency. To enable agri-food systems players, policy makers and researchers to assess the sustainability of current and future practices and products, methods of evaluation, and notably Life Cycle Analysis, should be improved to capture interactions between crop and livestock in a circular economy, to be applicable to production systems, territories and diets and to allow for proper evaluation of biodiversity, economic and social performances of value chains (see key area 4).

1.3. Efficient and safe utilisation of manure

Despite previous studies, there is still a lot to be done in a new context to turn manure from a former waste to a valuable resource in circular approaches, while the largest source of ammonia emissions to the atmosphere is ammonia arising from livestock manure. Slurry storage of manure also results in significant emissions of methane during storage. In addition, in intensive livestock farming regions, farm size is undersized in relation to the quantity of effluent.

Supporting a more efficient use of manure by minimising nutrient losses (notably ammonia and particles) from slurries through the understanding of emissions, mineralisation and diffusion mechanisms of carbon, nitrogen and phosphorus. This requires to:

- Integrate all stages of the management chain, from animal nutrition to land application, including in buildings (litter, aeration, early phase separation), processing, storage and their integration into cropping systems and manure additives and systems to reduce emissions of ammonia and methane because some practices that decrease ammonia (NH_3) emissions can increase methane (CH_4) emissions. Modelling makes it possible to understand and predict the dynamics along the chain. Research and on-farm demonstration is also needed to progress some of the elements of the management chain, and where new and improved systems are needed (e.g. additives and systems to reduce emissions).

- Deepen the knowledge in the case of composting with an aim to make manure safe, and reduce odours as a source of organic matter input to soil, the effects on the dynamics of carbon and nitrogen in soils need to be assessed precisely and the volatilisation of amonia reduced.

- Evaluate the consequences of manure application on soil microbiome, biodiversity (invertebrates, microbial population) and biological functions, the dynamics of carbon and nitrogen in soils, and volatilisation of amonia. A major factor is manure presentation (liquid, solid, composts) and application. New practices of manure management must be evaluated. Research must also highlight to which condition legislation can help to better manage manure.

Ensuring a safe use of manure and organic waste

Livestock manure can convey biological (pathogens, antibiotic resistance genes), organic (pharmaceutical residues) and inorganic (copper, zinc) contaminants. There is a need:

- for a better understanding of the impacts of land application of manure with regards to contaminants (dissipation vs. accumulation, transfer into the food chain) as well as impacts on health, environment and soil biology.

- To study, in addition to the work on livestock management to reduce drugs use and the presence of residues in effluents (see SD2), the effects of management methods and spreading practices to limit the risks.

Innovative manure refinery technologies within a circular economy

In intensive livestock areas, surplus of manure has to be transformed or transported over large distances to regions with nutrient deficits.

- Compare the various treatments known to increase the transportability of effluent in terms of energy demand and environmental impact.

- Study innovative value chains for manure valorisation: extraction of organic acids for chemical industries, ligno-cellulosic compounds for the production of fibres, proteins and other nutrients for insects, algae and bio-fertiliser production and water for irrigation thus drastically limiting the volume to transport. New processes have to be developed and the balance between the extraction of molecules and the agronomic valorisation of the by-products should be evaluated.

- Evaluate the balance between biogas production and the agronomic quality of digestates, notably their effects on soil carbon stock and nitrogen use efficiency, like a reverse engineering to adapt digestates to the needs of agriculture. Effects of insertion of a biogas digester in a territory on the functioning of agriculture (change of cropping systems), interactions between farms (logistics), on governance and social acceptability are important questions.

1.4. Support the role of livestock in organic farming**

In organic farming, integrating livestock and crops at local level are key for providing organic fertilisers for crops and feed for livestock. Organic farming together with local production are well regarded by consumers but on the other hand, organic animal husbandry raises some specific issues notably because animal efficiency is relatively low.

Towards climate smart organic livestock systems

Optimising grassland use in herbivorous systems, including restoration of abandoned grassland. Better understanding the effects of feed diversity on animal performances will contribute to efficiency: more biodiverse grassland and forages able to stimulate foraging behaviour while providing resilience to climate hazards. Selection of animal genetics (ruminants and horses) well adapted for grassland-based systems and the provision of more balanced concentrate feed with suitable protein and amino acids composition are another way to progress. Increased soil carbon sequestration thanks to grassland, legumes, agroforestry and improved manure management will further reduce net emissions, notably nitrous oxide (N_2O) and ammonia (NH_3) emissions, and energy consumption. Finally, the evaluation of organic farming systems should be fine-tuned, to embed environmental services and better allocate GHG emissions between food production and other services.

Improving sustainability of low input monogastric systems

The search for increased efficiency reinforces priorities for breeding schemes for low density diets, foraging behaviour and robustness (notably piglet survival). There is a potential to improve nutrient efficiency in organic animal production by innovative production of high-quality protein and amino acid feeds from green, blue and red sources and by development of innovative bio-refinery methods. The development of outdoor systems including walking areas, innovative housing is a social demand but to what extent keeping animals in a more natural environment contributes to animal health and welfare and is compatible with environmental issues should be evaluated. Walking areas can be diverse and should provide shade (e.g. oak tree grassland for pig, orchards where poultry are able to contribute to plant biocontrol by eating insects). Production and management of straws are a keystone both for animal welfare (litter) and the production of compost for soil fertility.

Achieving a circular economy in organic farming requires gains in efficiency and resilience, breeding strategies and methods towards increased genetic diversity allowing adaptation to local conditions, ability to use a diversity of crops/biomass, resistance to diseases, tolerance to various stresses and high vitality of young animals.

- Feed production should look at the inclusion of new and old species and varieties targeted to local production and innovative grassland-based ruminant and horse systems balancing dietary needs through a diversity of roughage sources.
- Mixed farming (different species/ breeds, livestock and crops) to increase resilience and feed efficiency needs to be assessed in organic farming and better manure processing and handling, notably compost, can contribute to improve soil fertility. Development of networks between organic farmers will facilitate organisation of (knowledge) exchanges, supporting the implementation of the CAP.
- There is a potential to improve animal health through management strategies and housing systems that prevent infections, illness and mortality, and feeding and breeding strategies that support animal robustness towards infections and diseases. In animal health, improvements are expected from the use of plant bioactive compounds (biorefinery, curative and preventive uses).

Expected impacts

- Rejuvenated agriculture encompassing circular and efficient food production systems,
- A circular agriculture with efficient resource-use at system level that reduces wastes in the feed and food chain and closes the nutrient cycles,
- Increased soil carbon sequestration and improved soil fertility,
- Increased European protein self-sufficiency and less European protein imports,
- Reduction in the use of mineral fertilisers and biocides,
- Reduced water scarcity,
- Mitigated GHG emissions, towards a climate or temperature neutral livestock sector,
- Increased resilience of farming system with regards to climate change,
- Increased agro-biodiversity and preservation of wild biodiversity,
- Improved agronomic value of manure and innovative use of manure in circular economy,
- New local business models based on integrated cropping and livestock systems,
- Local production of a broader range of food and feed products offering new sales opportunities,
- Animal health supported by plant secondary metabolites produced,
- Improved sustainability of organic farming systems with livestock,
- A more holistic view of the impacts of animal production on the environment,
- Europe as a frontrunner in new solutions for circular approaches and climate smart agriculture.

2. Animal health and welfare

Challenges

Animal health and welfare are key elements in gaining consumers' trust in livestock farming systems. Much research deals with the concern of infectious diseases, the transmission of zoonotic pathogens to humans and the development of curative approaches[23] with the objective to achieve a more prudent use of antibiotics in a One Health approach. ATF strongly support all the initiatives. However, there has been less emphasis on integrated management of animal health and animal welfare or on the links with human well-being in the concept of One Welfare[24]. The central objective is to position animal health and welfare as major levers of the multi-performance objectives of animals and livestock farming, taking into account functional compromises and socio-economic evaluation of costs and benefits for farmers, product quality, environment and society. Research, innovation and dissemination into those areas require multidisciplinary approaches and should be conducted in close partnership with end-users of innovations.

It is crucial to mitigate antibiotic resistance in a context of strong connections between animal and human health and the rapid expansion of antibiotic resistances genes. Overuse of antibiotics has also shown indirect consequences on microbial ecosystems, other than the targeted pathogens. A major breakthrough in improving animal health and reducing antimicrobial use will be the introduction of ecological approaches in animal health management. Current and new knowledge can be used towards the coexistence of humans and animals with their mutual pathogens, either by developing immune capabilities of the host to contain or eliminate pathogens, or by promoting commensal microbial ecosystems of hosts that are capable of reducing or even preventing infectious disease including zoonoses. Finally, acurate monitoring of pathogens transmission requires that anthropogenic (climate change, globalisation of trade) and biotic risks linked to new animal husbandry practices (e.g. exposure to contaminants and wildlife) be taken into consideration.

Research by ethicists and physiologists concluded that welfare should refer to the state of the individual in its environment, including unpleasant and positive perceptions[25]. Therefore, livestock systems should not only strive to avoid animals' negative perceptions (mutilation, pain, fear and frustration) but move from stress elimination to positive emotions and the expression of natural and individual behaviour. This also raises the question of the personality of each animal. Research will inform public debates with objective indicators of animal welfare based on their perceptions according to different husbandry, transport and slaughtering conditions.

The link between animal health and welfare needs to be deciphered. While it is clear that animal health affects animal welfare, effects of improved welfare on health are poorly documented. We propose to reinforce the research on the interplay between health and welfare beyond on-going projects[26] and in support to the new partnership[27].

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[23] DISCONTOOLS https://www.discontools.eu/; [1] https://prezode.org/

[24] [2] One Welfare https://www.onewelfareworld.org/

[25] ANSES (2018) definition of animal welfare: "The welfare of an animal is the positive mental and physical state related to the satisfaction of its physiological and behavioural needs and expectations. This state varies according to the animal's perception of the situation".

[26] PPILOW https://cordis.europa.eu/project/id/816172; EU PIG https://cordis.europa.eu/project/id/727933; HENNOVATION https://cordis.europa.eu/project/id/652638

[27] https://research-and-innovation.ec.europa.eu/system/files/2022-04/ec_rtd_he-partnership-pahw.pdf

R&I priorities

2.1 Considering cognitive and emotional capacities of animals to improve management practices

The aim is to understand the positive and negative interactions between welfare and health in order to propose new animal husbandry practices that ensure animal welfare and health and to contribute to the quality of life of farmers. This research is supplemented by basic knowledge on animal biology and physiology and the science of cognition and behaviour developed in the cross-cutting issue (see 5.3).

Improve farming practice using animal capacities to perceive its living environment. From better knowledge on the capacities of livestock species to perceive the environment, carry out learning, memorise, interpret information, it is possible to improve management practices based on animal. This requires to:

- Characterise positive mental states, their behavioural and physiological expression in relation to husbandry conditions and practices and define and validate indicators of positive emotions and welfare, beyond the absence of stress and pain.

- Understand the behavioural robustness and analyse the balance between negative and positive states throughout the animal's life. Robustness requires control of the situation to arbitrate between meeting the animals' needs and adaption to constraints: "homeostatic" compromise, emotional control, cognitive control. Does the animal perceive the unexpected events in its environment differently according to its own personality? Should animals live in a cocoon without stress at any time? Is it necessary to have a few negative experiences in order to better manage such experiences later? What is the contribution of positive emotions to the development of the animal's quality of life and its robustness? How and in which situations can the animal change its own environment to enhance its own welfare?

- Analyse the impact of the enrichment of the environment or the transformation of livestock farming methods (i.e. feed, social, human, cognitive, reproductive aspects, etc.) on animal welfare on short, medium and long term. Today knowledge is limited to short-term effects and for limited enrichments in quality.

Understand the animal's awareness of its state to improve farming practices. Today we do not know if the animal perceives that it is sick, and we have no knowledge whether it can show pre-clinically behavioural signs of illness. Research is needed to:

- Early detection of the appearance of disorders through direct observations of changes in behaviour, declines in performance, emotional or cognitive tests, or more subtle physiological changes (i.e. heart rate, activity rhythm, social isolation, etc.). Digital technology, notably imaging and artificial intelligence can be very helpful tools to detect significant signals from background and raise alerts.

- Study whether there are self-medication behaviours in domestic species (as has been shown in wild species) and other behaviours likely to contribute to health and welfare (as parasitic avoidance or search for grey areas).

- Improve the welfare of sick animals through appropriate practices (i.e. specific enrichment of the environment to stimulate animals). This approach can also be developed in certain health management situations, notably during pandemic crises when confinement is required which may seem contradictory with certain behavioural needs of animals.

Exploring links between animal welfare and human well-being in animal production ('One Welfare' concept). We need to explore the links between human and animal welfare in livestock farming to deepen what issues are driving both, how can understanding one of them improve the other. The consequence of the improvement of animal welfare on farmer well-being is an issue. Many scientific disciplines are required: animal production, veterinary and human medicine, ethology, ergonomics and organisational sciences, sociology, psychology, educational sciences and teaching of socially sensitive issues. The research concerns are:

- Explore the links between animal welfare and farmer well-being in livestock farming to deepen what issues are driving both, how can understanding one of them improve the other. Understanding the consequence of the improvement of animal welfare on farmer well-being is an issue.
- Understand why and how livestock farmers seek to change their practices, or even their production systems, to better take into account animal welfare and to what extent this improves their quality of life at work and their relationships with animals.
- Better understand the reverse side: how the animal can change its own environment to enhance its own welfare (= concept of agentivity).
- Better understand how citizens construct representations of animals and farming systems, define who the most influential actors are and how they use scientific knowledge.
- Implementing new practices based on this knowledge and which adds to the expertise of livestock professionals and enable the recognition and valorisation of their work.

2.2 Managing animal welfare as a prerequisite for animal health

The mechanisms that can influence the physical health of animals in relation to mental health are very diverse depending on the health disorders considered. Animal welfare as a lever towards a reduction of the use of antibiotics covers psycho-neuro-endocrine mechanisms and physiological relationships that link positive or negative emotions on health and elaboration of these during lifespan. To better understand and master the mechanisms the following research questions must be addressed.

Deepening relationship between animal health and welfare. A key issue is the understanding of interactions, synergies and trade-offs between animal welfare, the immune system and animal health. We need to:

- Understand trade-offs/synergies between welfare, health and efficiency (feed efficiency, production, reproduction, adaptation). This covers short and long terms as well as the entire life (career) of the animal with special attention to be paid to prenatal and juvenile periods, transition phases in young and adults (weaning, pregnancy...).
- Explore to what extent improving animals' welfare as compared with the existing systems would have an impact on the immune systems and the resistance to infectious disease, and/or infectious disease pathology with ultimate benefit in reducing recourse to antibiotics and diminishing the risk of zoonotic disease transmission. This is to prevent the deterioration of physical health due to negative mental states of animals (breeding diseases, consequences of physiological disorganisation, presence of infectious agents, including those with zoonotic potential, ineffectiveness of certain behavioural treatments).
- Conversely, consideration should also be given to health problems that may arise from innovations designed to meet the behavioural needs of farmed animals. Exposure to outdoor environments aiming to improve animal welfare may increase the risk of infectious diseases for which mitigating biosecurity measures (e.g. against African swine fever, avian influenza, diseases affecting wildlife) need to be adopted. Analyse the effects of acute or chronic behavioural disturbances and their mitigation on the physical health of animals.

Exploring interactions between individuals. In a context where animals are increasingly kept in groups and have privileged access to outdoors, we need to:

- Understand how interactions between individuals, and between individuals and their environment, impact the health and welfare of animals by considering positive emotions, microbiome flows, pathogen exchanges between animals and their environment.
- Understand the effect of the social position of an individual in a social network and at the group level on the susceptibility to infectious diseases or abnormal behaviours to understand how fast a disease or an abnormal behaviour will be transmitted within the network. The development of contagious models inspired from epidemiologic studies can help analyse animal social behaviour.

Knowledge integration will contribute to assess the complementarity of different levers (e.g. genetics, nutrition, microbiomes monitoring, husbandry practices, health and welfare management, digital technologies) at animal and group levels, towards more robust animals resilient to infections and pathogen related production diseases. For instance, new concepts may combine genetics and epidemiology to study how the genetics of individual affects the spread of infectious diseases, both within an animal and between animals, and develop innovative and integrated approaches for health management.

2.3 Management of immunity and microbiota for improved animal health

Many polymicrobial diseases, including respiratory diseases and parasitism, can affect the gut microbiota and the welfare indirectly through several mechanisms involving inflammation, gut-brain axis and microbial metabolites. In a context of climate change and a more prudent use of medicinal inputs, it is essential to have a good understanding of the animal's ability to adapt in stressful situations.

Characterisation and management of animal immunity in its environment. Our knowledge of the immune system of livestock remains well below the knowledge in model species (rodents) or humans. The specificities that characterise farmed animals must be better known because they have a direct link with disease resistance and the efficiency of vaccination.

- Understand the immune potential of animals and their ability to return as quickly as possible to a physiological state of balance (health history, breeding practice, diet, commensal flora).
- Discover and exploit new antimicrobial, antiparasitic and antiviral pathways in livestock immune cells that could be harnessed to overcome microbial, parasitic and antiviral subversion of host immunity. This includes domains of research with high potential, such as inflammasome activation, immunome-tabolism, lipidomics, mitochondrial dynamics and metal-centred antimicrobial systems. Better understand the immune potential of animals and their ability to return as quickly as possible to a physiological state of balance (health history, breeding practice, diet, commensal flora).
- Know the genetic determinism of the variability of the individual immune response (including vaccine responses) and identify as early as possible predictive biomarkers associated with animal resistance to a broad spectrum of diseases (to be adapted according to the species, type of breeding) to find the right compromises.
- Identify biomarkers of a healthy (innate) immune system in relation to feed efficiency, disease prophylaxis, pathogenesis and animal welfare.
- Understand the respective roles that host genetics and epigenetics play in the carriage of pathogens (identification of biomarkers for low and super-shedders).
- Investigate the genetic diversity of circulating pathogens and its correlation with their transmission and virulence, including the vectorial competence of arthropods in the field for pathogens at risk of emergence or already

circulating. Conversely investigate the genetic variability of the host for pathogen. Epidemiogenic is a new and promising field of research.

Regulation and function of microbial communities (microbiomes, pathobiomes) in relation to animal health and welfare[28] in ecosystems linked to livestock (host microbiomes) or not and their role in the preservation of animals, humans (zoonosis, etc.) and environment (wildlife, vectors, reservoirs, etc.) health. This should lead to the development of new strategies towards livestock and human welfare and health, eco-health, as well as novel prophylaxis and therapies. This requires to:

- Develop knowledge about microbial communities (structure, composition, function) that are the most beneficial at different stages of the animal's lifespan, about biotic and abiotic parameters that influence their composition, across different microbiomes (lungs, intestine, skin, reproductive system, etc.) and between animals (of a group or through generations). This covers interactions between commensal and pathogenic bacteria and viruses to understand the barrier function (e.g. salmonella in poultry).

- Understand the host-pathogen-microbiome interactions at the organism and cellular level to determine how pathogens overcome the host barrier effect and how we can counteract this property. Development of knowledge and monitoring of the relationship between gut health, the immune system and brain functions (with consequences on cognitive and emotional capacities), knowledge on the relationship between host genome and microbial metagenomes will help develop innovative practices (including pre- and post-natal periods). To decipher the numerous interactions, the use of organoids is a powerful tool. Development of knowledge on how the microbiota (complex, synthetic) and/or the host limit pathogen colonisation at the cellular level (cellular models, organoids). This task is key to determine the key factors that lead to the super-shedding phenotype (host genetics, gut microbiota composition and function, immune status...).

- Management of microbial ecosystems: namely beneficial commensal communities to prevent pathogenesis, monitoring of pathogens (early detection, traffic tracking and identification of transmission sources, risk management, prophylaxis, cost-benefit assessment of solutions). The aim is to define strategies and means for piloting microbiota development and evolution and immune defense to benefit health, which includes the use of pre and probiotics, immuno-stimulants, feeding and housing strategies at different stages of life, as well as controlling transmission from one animal to the next one. The use of phages and synthetic microbial communities are other (more prospective) possibilities.

2.4 Towards responsible livestock systems that guarantee animal welfare and health

The aim is to propose solutions that jointly preserve animal and human health and welfare, while safeguarding food safety, environmental health and farm economic profitability.

Develop and test improved rearing practices and processes at farm level. To assist in the design of new practices and systems that maximise welfare and health throughout an animal's lifespan, it is necessary to identify balance and trade-offs between health and welfare that minimise the impact of changes in practices on other performances. This requires to:

- Develop alternatives to painful practices: optimising welfare in dairy calves and dams at post-natal separation, alternatives

[28] The HoloRuminant project prefigures this new approach to global health in the case of ruminants: https://holoruminant.eu/

to farrowing crates for pigs, preventing aggression in pigs and poultry, outdoors access, sustainability of loose housing systems for laying hens. Limiting the stress during the farm to slaughter phase is an important issue that can affect quality of ASF.

- Promote practices favouring the expression of positive experience and natural behaviour with positive impacts to reduce diseases: identification of situations that promote positive experiences (i.e. creation of groups of animals according to affinities). The adaptation of transport and slaughter conditions in connection with knowledge of the state of awareness of animals is part of this issue (i.e. the role for small mobile slaughterhouses).

- Evaluate husbandry practices that allow the establishment of microbiota with a health-protecting effect, starting with hatching/partum conditions and the proximity of mothers and young in postnatal phase.

- Explore the value and establish indicators of desired diversity of genotypes[29], species, breeds and individuals to increase resistance from animals to disease and heat waves and the resilience of systems.

- Develop innovation for breeding (by developing epidemio-genetics approaches), management-support and surveillance of free-ranging livestock with a special focus on prevention against wild fauna (large predators).

Develop more efficient strategies for a more prudent use of antimicrobial. Strategies must be developed to mitigate the use of antibiotics and antiparasitic drugs and limit the resistance to antiparasitic molecules that reduce the effectiveness of the drugs and increase the risk of disease transmission in all species. The research priorities are to:

- Review of vaccination prophylaxis with regard to the evolution of breeding practices (return to the ground of hens, etc.), depending on the genotype, etc.

- Study the effectiveness of functional nutrients (fibres, micronutrients, milk and colostrum messenger ribonucleic acids (mRNAs) and stems cells, etc.), alternatives to medicinal inputs (essential oils, herbal medicine) and natural immune-stimulating molecules to strengthen the immunity and robustness of animals and the effectiveness of vaccines.

- Study the host-directed therapies for management of infectious diseases in farm animals. To replace mass culling following detection of regulated diseases, personalised veterinary medicine inspired by omics, artificial intelligence and organoid models could be used to develop sensitive biomarkers for early detection of index cases, propose farm animal host-directed therapies to help animals to combat infection and pilot animal ecosystems to reduce pathogen shedding in the environment.

- Develop innovative pathogen-directed therapies for management of infectious diseases in farm animals.

- If antibiotics are to be used, develop innovative pharmacology approaches including better timing of administration, taking account of physiological status or chronobiology associated with earlier detection of diseases for more targeted interventions.

- Study the drivers and obstacles to the implementation of improved farming practices and transitions towards sustainable animal health and welfare systems and practices including work organisation and the conditions for their economic viability.

Develop valid, reliable and feasible indicators and Decision Support Systems to manage animal health and welfare. These developments are required for a better monitoring of animal health and welfare, allowing real-time monitoring of individuals or

[29] After the GenTORE project dedicated to ruminants: https://www.gentore.eu/

batches of animals on farm and in experimental facilities where initial proof of concept has to be identified (see key area 6). This concerns:

- The development of new indicators of poor or positive animal welfare in a variety of species across a variety of production systems and based on an in-depth knowledge of the animal's perception of its environment both during farming and also during transport and at slaughterhouse. The indicators should be developed with experiments in controlled condition and tested on farm using participative research. It should be noted that the development of new indicators is also required to improve animal welfare during experimentation using infectious challenges. This includes the use of individual animal monitoring and biosensors for combined analysis of behavioural and physiological parameters.

- Mobilise sensor technologies, automatised collection and analysis of data (physiological constants, odours, sounds, imagery) and artificial intelligence which are powerful tools to detect malfunctions quite early. This also encompasses the development of user-friendly feedbacks to farmers regarding welfare and health indicators. Sensor technologies can also be used during transport and at slaughterhouse.

- Develop on-line disease-diagnostic systems and efficient non-invasive diagnostic tests/devices to identify a specific pathogen, measure physiological constants operating on farms and offering farmers and veterinarians an optimal basis for a targeted prevention and/or treatment of sick animals. Many avenues for improvement are expected from combining and assembling data from potentially widely differing types and varied sources into meaningful indicators.

Develop precision management technologies to improve animal welfare, health and efficiency. Digital technologies allow early warning and real time management and could provide useful information for better management of animal welfare and animal health. Development of new technologies and digital solutions (imaging, sensors, robotics, IoT and high-tech, artificial intelligence models, digital twins) are an integrated part of this domain of research.

- Use IoT to improve animal management: develop indicators and/or proxies to adapt feeding and farming systems from group-based to individual-based models, management of individual animal diversity considering lifespan, scale of application, genetics and monitored performances. Feed efficiency can be improved by genotype-based management and by using temporal variation to control animal feeding.

- Animal use of IoT: understand how animals learn using automation (e.g. self-feeders, etc.) and also conversely, how this automation can allow the animal to adjust its own environment for its health and welfare.

- Evaluate (notably in dairy and pig production) the gains made possible by the management of individual diversity instead of the management of a “mean animal” based on the information available in dynamics and by combining the knowledge of genetic diversity offered by genotyping possibilities now available and phenotypic diversity of animal trajectories.

- Evaluate the return on investment of these technologies[30] via the development of bio-economic models and the evaluation of the real interest made possible by the acquisition of new information (cost reduction, saving of working time, etc.) in relation to the upstream investment.

Transition towards local and value chain organisations that guarantee animals’ health and welfare throughout their lifespan. Technical and organisational innovations as well as legal, economic and institutional processes and coordination mechanisms between stakeholders need to be

[30] This point was mentioned as a priority by the EIP-AGRI Focus Group on Precision Farming (2015)

implemented at these levels to move towards better consideration of health and welfare issues (including when animals move from one farm to another). This concerns:

- The study of the effects of different forms of coordination and of globalisation of agricultural and agri-food markets, the evolution of organisational forms according to various types of systems (e.g. co-existence of confined and open-air farming systems), the strategies of stakeholders (living with or eradicating pathogens), knowledge produced on health monitoring (e.g. interaction with wildlife) and technical innovations. These changes must take into account the full diversity of farms.

- This issue also encompasses the design of systems aiming to monitor and manage emerging infectious diseases and behavioural disorders related to animal welfare, using new surveillance tools (e.g. precision breeding for example or powerful digital PCR test for detecting circulating pathogens directly on the farm (surfaces, soil, wastewater, etc.)). Current high throughput technologies allow a tenfold increase in our ability to predict the risk of infections (i.e. emergence of variants, environmental reservoirs, carriage by wildlife...). This allows us to detect pathogens before clinical signs manifest and distinguish the virulence of strains, pathovars, variants or pathobiomes. The use of updated *in vitro* models (organoids) of farm animal species will enable us to better predict the pathogenicity of new circulating variants and reduce the need for *in vivo* experiments, thus saving animal lives. They will also make it possible to test and predict the efficacy of treatments.

Expected impacts

- ➢ Improved animal welfare and health in livestock production systems,
- ➢ Improved ethics and appreciation by society of livestock production systems,
- ➢ Development of innovative concepts and preventive strategies integrating complementary levers (e.g. genetics, nutrition, microbiome monitoring, husbandry practices, health and welfare management, digital technologies) to ensure animal health and welfare,
- ➢ Development of innovative health and welfare practice guidelines,
- ➢ More prudent use of antimicrobials, reduction of dissemination to the environment and reduction of antimicrobial resistance,
- ➢ More efficient and "country tailored" surveillance systems,
- ➢ Better implementation of animal welfare and health monitoring throughout the production chain,
- ➢ Objective assessment of animal welfare,
- ➢ Emergence of new value chains and business models, increased farm revenues and resilience,
- ➢ Support to the livestock industry to open up doors, build corporate responsibility and become transparent in a way society understands,
- ➢ Facilitation of free trade of animals and their products throughout Europe and strengthen the European livestock sector's position.

3. Food and nutrition security in One Health approach

Challenges

A paradigm shift is required for research on the quality of ASF considering the "One Health" perspective. It needs to address not only intrinsic qualities of products (health, nutrition, flavour, processing technologies) but also their extrinsic qualities linked to production and distribution methods to which consumers are increasingly sensitive. This brings new research questions. Several studies conclude that the consumption of animal products needs to be reduced (sometimes drastically) but the consequences on physical and mental health in relation to nutritional needs of categories of population, as well as economic and social development of territories remain poorly informed. Dietary implications, and more generally impacts on sustainability of alternative proteins are also largely unknown. New questions also appear on the quality of animal products throughout the chain. One challenge is to identify levers and design systems fostering the desired (sensory, nutritional, sanitary, technological, commercial) qualities throughout the chain. In a context where systems and product differentiation allow adaptation to the heterogeneity of consumer preferences and incomes, another challenge is to evaluate how more agroecological/smaller scale production systems will impact product quality and variability and the organisation of the processing industry. Finally, unexplored opportunities exist to make the best use of animal biomass in a circular bioeconomy. A large area of research and innovation lies in the valorisation of livestock-based products for nutraceutical and non-food use with a view to reducing food waste. A growing body of scientific evidence shows that eggs, milk, meat and carcasses are sources of active molecules that are of major interest for human health and different food and non-food industrial areas. These biomolecules can be advantageous substitutes for certain synthetic chemical molecules and may address consumers' demand for more natural products.

R&I priorities

R&I priorities aim to benefit from the assets of livestock-based products in more sustainable and healthy diets. Most of the R&I priorities were jointly developed with the Food for Life European Technology Platform.

3.1. Improving insights into consumption of ASF and human health***

Deepening the knowledge about the effects of ASF on human physical and mental health

There is a lack of data on the benefits and drawbacks of dairy products, white and red meat and eggs in a diet considering the supply of micronutrients, bioactive compounds (e.g. creatine, collagen) or anti-nutrients in a context of reduction of the consumption of ASF.

- Further insights on dietary requirements according to different population segments as well as on the healthiness and risks associated with more or less restrictive (vegetarian, vegan or omnivorous) diets in the long term. Concerning cognition, the effect of milk lipids (especially polar lipids) in cognitive development of children and the effect of a reduction of ASF in the elderly on a possible cognitive decline should be better understood.

- Better understand the effects (either positive or negative) of ASF in interaction with other environmental factors (infections, stress, pollution, etc.) and type of population in the mechanisms of inflammation and oxidative stress which are two vital functions of our body which allow us to live and also to defend ourselves against external attacks. The role of ASF to prevent or on the contrary to promote allergies is one important issue.

- Modelling the effect of a readjustment between ASF and plant-based food (including ultra-processed plant-based food) on the adequacy of nutrient supply and human health considering the different ASF (dairy, eggs, red and white meat, processed meat) and the most sensitive populations (young growing people, pregnant women, elderly people) and on the health of ecosystems, including biodiversity. This is in line with the concept of "one quality" developed by the EU funded project INTAQT[31], but broadening the approach to all types of ASF.

Alternatives to animal proteins

Innovations are very rapid in this domain (e.g. plant-based substitutes, *in vitro* meat, insect proteins). Research is needed to:

- Compare trade-offs on the nutritional value including bioavailability and anti-nutrients, as well as on the implications of processing and on the overall impact on consumers nutritional health of alternative foods.

- Develop foresight scenarios projecting market shares of alternative products and associated land use and environment impacts which are required to understand the consequences of a shift to alternative proteins sources.

- Develop insight in the role of ASF in diets in a context of demand for less processed food.

3.2. Management of nutritional, sanitary and sensory qualities of ASF***

Building the quality of animal products throughout the production system to advance human health and sensory qualities

Combined strategies (genetic, nutritional programming, regulation of gene expression, rearing) can contribute to produce ASF that have recognised healthier characteristics through focusing on components that have been shown to advance human health and improve sensory qualities. The strategies differ among types of ASF.

- Understand the biological construction of ASF nutritional quality. This concerns construction of quality of meat at different stages of the animal's life, at slaughtering and post-mortem, to identify predictors of quality and define the most appropriate conditions of rearing. For milk, innovation will arise from a better understanding of the development of casein micelle structures and properties of fat globule membranes (phospholipids, protein). For eggs, a better understanding of the genetic and biological mechanisms that control the solidity of the shell and yolk membrane is needed to propose egg rearing and storage routes that are favourable to quality. For ruminant meat, beyond the understanding of maturation process and variability between muscles, a promising area of research is the study of the dialogues between muscular, adipose and connective tissues for understanding the way they co-develop and determine the quality of the meat.

- Control the sanitary quality of products. Although rare, there are still accidental contamination of ASF. The study of food pathogens (bacteria, virus, parasites), their transmission through the food chain, their persistence in livestock and food industry remains a challenge. It is necessary to put emphasis on the chain-based approach to address variability in the animals which is increased by the hazards and sometimes in less-controlled systems. Among priorities: eggs which can be responsible for numerous toxic infections, study of the microbiota of the udder for milk sanitary quality, finishing techniques to eliminate possible toxic residues in the meat.

- Ensure simultaneously sanitary, sensory and nutritional quality of ASF and social acceptability of farming practices. Social demand calls for animal access to the outdoors for animal welfare reasons but outdoor production raises risks of contamination and of possible alterations of animal products. Farming practices, including animal genetics,

[31] https://h2020-intaqt.eu/

must be developed to seek the best compromises between these objectives.

Technologies to increase the nutritional value of animal-derived products

Beyond farm gate, nutritional and organoleptic quality of ASF can be improved by innovative technological process:

- Hydrolysis of muscle proteins could make it possible to foster the assimilation of proteins and the bioavailability of essential amino acids for certain populations. This may in particular help address sarcopenia in the elderly whose protein consumption may be below requirements.

- Study further the impacts of heat processing on nutrient loss (e.g heat treatment of milk, processed meat). There still is a need for research and innovations on mild processing of milk with a view to preserve native properties of the raw product while ensuring food safety.

Food systems dynamics

The diversification of production systems, even of farmed species (valorisation of animal biodiversity, autochthonous species/breeds, products with geographical indications, local food, organic food, etc.), leads to a greater diversity of products**.** This raises different questions:

- Understand how industries can adjust to a demand for more diversified, less standardised raw products, less regular production, possibly in smaller amounts. There is an issue around the capacity for the (already under pressure) conventional production system to adapt to down-scaling and on the impact on business sustainability. This could include the early monitoring of the product to decide the destination of the product (e.g. sensors or near-infrared spectroscopy/mid-infrared (NIRS/MIR) to predict the quality and adjust the process in the industries).

- Develop tools for improved traceability along the food chain to ensure transparency and mitigate food fraud, tracking and tracing. The challenge is to produce verifiable information regarding production processes on product labels. Also, authenticity testing with e.g. finger printing technologies isotopes, omics techniques, may help certify the origin of a meat sample in relation to geographic aspects or (outdoor) production processes.

- Develop metrics and methods to consider and evaluate together intrinsic and extrinsic qualities of ASF. This is likely in line with part 4.4 considering global evaluation of the livestock system but in this part ASF is not at the heart of the system.

3.3. Functional and bioactive properties of animal-source food and by-products***

Exploration of bioactive compounds of interest for human health

Animal-based products contain a diversity of compounds having relevant nutraceutical properties that need to be better known and exploited and could be enhanced by retaining new animal profiles. Priority concerns are:

- Eggs contain active molecules with antimicrobial and anti-carcinogenic activities.

- Milk compounds are said to have anti-allergenic properties (asthma, dermatological diseases) that need to be better known in a society where allergies are on the rise. This is due to its high content of highly digestible proteins.

- Meat is an interesting source of food for its bioactive peptides which would add value to low price pieces.

Non-food applications of animal product components and by-products

The carcass represents a source of proteins such as collagen, elastin and keratin with interesting properties of resistance (tensile strength, pH, temperature, etc.) and rigidity (bone, tendons, connective tissue, etc.) that are under-exploited. An exhaustive study of their functionalities and extraction processes would enable applications in biomedicine (haemostatic dressings), biomaterials and pharmaceuticals. The acquisition of genetic, biological and physical data on various eggshell models is a prerequisite for the development of potential applications in the field of biomaterials (use of additives or "natural" inspiration molecules). Milk components can also find numerous alternative applications in the processing of biodegradable bio-plastics, textile fibres, glues.

Expected impacts

- Evaluation of the effects of animal-source food on human health,
- Evaluation of nutritional, environmental and societal value of meat substitutes,
- Improved nutritional value of animal products through innovation at farming and downstream level,
- Innovative utilisation of products of animal origin both for human nutrition, as nutraceuticals and non-food applications,
- Evolution of food systems to fit more diversified demands,
- Improved products traceability and mitigation of food fraud,
- Improved consumer trust in animal-based products,
- Business models, license to operate, economic wealth.

4. Livelihoods and economic growth

Challenges

Livestock farming is at the nexus of several social and economic challenges and is concerned by several controversies, notably in the case of intensive farming. A deep analysis of these interdependent issues may provide a better understanding of the socio-technical and socio-economic transformations required for a more sustainable livestock sector. It may offer perspective to value chain actors to overcome challenges faced by livestock farming and to policy makers for setting up relevant incentives and regulations, instruments and policies to support a transition and overcome imbalances in value sharing across value chain actors. This may also strengthen cooperation between stakeholders at local (or larger) scales for the development of circular solutions to create new shared perspectives, partnerships and business models. To assess the sustainability of current and future systems and products, it is critical to define the baseline and to track improvements towards sustainability. Life Cycle Assessment (LCA) has gradually emerged as an internationally recognised approach. Originally developed for industrial products, LCA is a product-based approach. It has limitations with respect to measuring the interplay between products and activities. Sector-wide indicators need to move forward to take into account at least a part of the complexity of agricultural and food systems, dynamics of phenomena and services and disservices provided by agriculture.

To tackle these challenges of societal expectations, farm profitability, public support and environmental and social effects of farming systems, open-innovation and co-innovation are relevant approaches and ATF warmly encourage these new research approaches. Stakeholders must be involved in innovation processes and contribute to decision-making. The living lab approach is a tool well suited to the objectives.

R&I priorities

R&I priorities aim to understand socio-economic issues to highlight the future and how different farming systems can contribute to the provision of a variety of services to the society and support new pathways.

4.1. Drivers for the evolution of the livestock sector***

Dealing with the controversies regarding livestock farming

For several years, a movement against livestock farming activities has been developing, which is structured around four main areas: socio-economics, environment and climate change, human and animal health, animal living conditions and ethics of animal consumption (does human have rights over animals?), themselves broken down into sub-registers. Livestock farmers are trying to respond to these concerns without much success. The status quo is not an option.

- There is a need for scientific clarification, notably by cooperation between biological and human sciences (economics, sociologists, anthropologists, historians, geographers), of the terms of the debate which has become controversial and of the expression of this debate in the different European countries to identify the ways of progress to overcome controversies taking into account the convergences and divergences between European countries.

- Based on knowledge of biological facts and controversies, develop information methods and contents adapted to different audiences, to help them to understand the complexity of livestock farming and more generally of agriculture and that simplistic messages cannot lead to sustainable solutions. A particularly important point would be the content of school textbooks for the younger generations.

Understanding consumers' socioeconomic drivers, trends in markets[32] to gain precise knowledge of evolutionary trajectories of the consumption of ASF in Europe, the underlying motivations and how to curve it towards more sustainable lifestyles. Focus needs to be on:

- Studying intergenerational differences, stratification within populations, socio-economic and cultural situations, projected trends of evolution across countries and markets, production systems and living conditions of livestock vs consumers' willingness to pay, and changing dietary preferences.
- Understanding evolution of markets considering the shares for alternative products (e.g. plant-based products, insects, algae, cellular meat), consumers demand for local sourced food.

Knowing the markets demands to better guide the livestock sectors and public policies for strategic choices. For that purpose, it is crucial to better know the markets in third countries. This requires having:

- Better understanding and modelling of demands based on demographic and economic growth in various parts of the world.
- Better knowledge of possible developments in third countries animal sectors and their capacity to respond in quantity and quality to the demands both locally and within the EU via imports.

Livestock farmers' generation renewal which is a big challenge in all Member States. It is important to:

- Understand how farmers deal with change in their farms and society that impact their working practices, notably increased social demand for animal welfare, growing number of rules and regulations, relations with neighbours, new work organisation. Development and assessment of social indicators of farmer work is required.
- Understand how policies, market development, industries or new value chains based on business models that allow transparency, value sharing within agri-food chains steer farming systems.
- Evaluate the risks and benefits of digital technologies and robotics that can remove repetitive or painful tasks and bureaucratic control but at the same time can create new ones (maintenance/surveillance of equipment), which can be a source of stress and may reduce human-animal relationships and profoundly change the relationships with actors involved in consultancy and selection. In addition, these changes can modify the perception of welfare and relation between farmers and animals by the consumer and the citizen.

Understanding the determinants of structural changes in farms and industries and their consequences on livestock farming performance will inform scenarios of competitiveness, territorial distribution and ability to fit diverse demands. In particular, the low and variable prices of animal products and the health crises (influenza, swine fever, Epizootic Hemorrhagic Disease…) invite us to reconsider the question of farming models in connection to the organisation of sectors and markets to respond to the various demands of consumers. This involves:

- Understanding the structuring of sectors, the distribution of value (between strategy of maximising economy of scale, or economy of range, or economy of agglomeration, or segmentation based on better knowledge of the different markets and their size), the strategies of stakeholders and the coexistence and hybridisation between dominant systems and alternative systems.
- Understanding the role of the coordination between actors, and the influence of private (e.g. industry, retail) and public action (new food standards, policies on

[32] This topic was developed in collaboration with Food for Life ETP through experts' consultation

investment, risk management and process innovation) to create and share value.

- Analysing the competition or synergies between green energy production and animal feed production which remains a poorly integrated domain into economic analysis.

4.2. Diversity and diversification for supporting multifunctional farming

The diversity of farming systems and its evolution (diversification) has hardly been considered as an objective of research. Farming systems diversity is often seen as very positive to foster the resilience of livestock systems facing new challenges, to limit the consequences of pandemics and as a key element for the transition to agroecology but there are still poor demonstration of the advantages and limits of this diversity, and adequate indicators of a desired diversity. The role of consumers and food chain actors for system diversification must also be deepened.

Characterise and study the management of the diversity (and diversification) of livestock systems are central points to increase resilience of livestock sector and ensure a diversity of animal-source food that meet consumer expectations.

- Diversity should be described and evaluated as a source of adaptability and resilience at farm, sector and regional scale, as a source of production efficiency and consistency or not, as a source of ecosystem services as well as disservices. Insights on the complementarities, synergies, tensions, competition, and commensality between systems are needed.

- The respective role of farmers' motivations, collective action and public action in diversification of farming system must be better quantified and understood.

- The reintroduction of livestock farming in areas where it has disappeared is a main issue for diversification and is a matter of great importance from an environmental point of view. We need to determine which production systems, which social organisation between stakeholders can run successfully and how to maintain and support this diversification from an economic and social point of view. This concerns the reintroduction of livestock farming in cereal plains and under perennial crops (orchards, vineyards) and what type of animal production is best suited (species, farming methods). Concrete cases could be studied within the framework of the "Agroecology" partnership.

- Management of the diversity also requires a reorganisation of advisory and extension services. The question that arises is "how can agricultural advisory system be reconfigured to cope with the diversity and to accompany the diversification of livestock farming systems?". It entails a capacity to support farmers in developing their specific business model at the articulation between inner strategic processes and investments in territorial sectorial dynamics.

Studying the role of consumers demand to design innovative livestock systems

- Develop insights into consumers' appreciation, expectations and willingness to pay for product diversity, and into the capacity and willingness of processing and retail industries to manage diversity of products. This could range from the creation of new segments by the downstream sector to the promotion of new production to the farmers' marketing for heterogeneous products and the capacity of downstream structures to address heterogeneity.

- Study the role of labelling and traceability of product and production system for consumers choices and sectoral organisation must be better quantify.

4.3. Governance of the livestock sector to promote change over time

The transition to new systems is not only a matter of technological innovation but also of organisational and institutional innovations notably when considering the search for new synergies between livestock and crop sectors or for the development of a biosecurity strategy. It requires new perspectives to be shared and new partnerships, new economic models and new social organisations implemented. The question that arises is "how to manage this diversity without jeopardising the coherence of the sector?".

Studying the coordination between stakeholders to change the socio-technical system. To break out the "locked-in", it will be necessary to target coordinated innovation at different levels in parallel. The mains issues are:

- Analyse (benchmark) of case examples of systems in transition to identify conditions and factors that promote the success of new organisations, new value chains, learning processes and, on the contrary, lock-in phenomena. This covers the exploration and demonstration of business models to integrate innovation into local circularity approaches and the development of new value chains, including organisation of a fair and efficient repartition of added value and management of health issues.

- Study of the coordination challenges arising from the combination of individual initiatives and collective approaches which are likely diverse and have few precedents. The role of the coordination between stakeholders involved in the development of agro-ecological practices should be better described. Cooperation, on a territorial scale, between farmers, food chain stakeholders and other stakeholders (residents, local elected officials, NGOs) are all essential questions for the integration of livestock farming into the territorial circular bioeconomy. The evaluation of how collective action of neighbouring farms affects sustainability at the local level is important.

- Understand how actions at different governance scales need to be taken for an effective change of the livestock sector for a circular approach, to develop coherence between regional production and markets, and to highlight the synergy and trade-off between different policies notably between livestock, climate objective and bioeconomy strategy.

Providing knowledge to help to design of public policies (CAP and local/regional policies) to facilitate transition. Public policies must encourage changes and facilitate transitions, the emergence of new value chains and cooperation between stakeholders. The regionalisation of solutions is a central point which implies, beyond the CAP, the development of local policies.

- Study of specific measures to "protect innovation niches" during the experimentation period and the structuring of practices and actors thanks to investment aids, tax exemption measures, support for the networking of actors.

- Define the most appropriate tools for transitions: payment for environmental services, other incentives, taxes and regulations. Among others, one important issue is to highlight the question of European and more distant biodiversity (deforestation) for which no unified indicators exist whereas reducing imports of soya and increasing crop diversification in Europe will dramatically change this performance.

- Assess the consequences of new policies in terms of production and consumption, trade, income (for different sectors and different social categories), changes in agriculture and agri-food occupations, public policies and regulatory systems and, ultimately, effects in terms of health and environmental risks for the different populations at risk.

Deepening the articulation between agroecological and digital transitions

By increasing our capacity for modelling and anticipation, digital technology is expanding our capacity for action and might decrease work burden. These information systems are increasingly diversified and used for a variety of purposes that evolve over time. The technological aspects can be supported by the

“Agriculture of Data” partnership but this technology also raised questions for a social point of view not considered in the partnership. Digital and data technologies present a risk of enclosure and a threat to democratic projects as it constrains representations and promotes the automation of decisions. Precision agriculture mobilises a system of strong actors that is totally different from what could be achieved through the networking of territorial agroecologies. Benefits of these systems should be more precisely quantified owing to their cost[33](the benefit of this system is not only economic) as well as the challenges related to data security, information imbalance, access to information, balance of power between stakeholders and risk of technological bias.

4.4. Evaluation of livestock farming systems to help them progress */***

Improving multi-criteria assessment of livestock production systems[34]

LCA attributional methods must be improved by developing a holistic vision of sustainability. Current LCA follow a linear way of thinking which makes it difficult to account for circularity, strong interactions between products and activities and agroecological approaches which are always in tension between the global impacts which are not very favourable to them and the local impacts, which are more favourable, but for which we do not always have effective indicators. In addition, advances at one level (animal level as it is the case in LCA analysis) are not necessarily beneficial at higher level. We need to:

- Include time dynamics processes to integrate phenomena taking place over long periods but crucial for the sustainability on a long-term basis (e.g. soil fertility, carbon sequestration, erosion, biodiversity); resource efficiency considering the recycling role of livestock and their capacity to value non arable land.
- Consider the spatialisation and regionalisation of phenomena to integrate the local carrying capacity of ecosystems.
- Test different allocation procedures and system expansion to properly evaluate the interactions between the different farming activities in mixed crop-livestock systems and to consider the production of ecosystems services beyond ASF provided by livestock farming systems.
- Develop social and economic indicators and a food/nutritional basket approach to consider nutritional value of food.
- Develop consequential LCAs to offer tremendous perspectives but it is still insufficiently developed to evaluate *ex-ante* scenarios concerning the place of livestock in value chains.

Developing multicriteria assessment using the “package of services” concept as a framework for research on livestock systems

The concept of package of services aims to describe livestock systems’ economic, social and environmental performances, to understand the biological, technical, cultural and economic determinants and analyse synergies and antagonisms between performances. This approach will make it possible to address trade-offs between services and disservices, relationships between services and the resilience of systems, evaluate avenues around circular territorialised approaches in livestock farming, interactions between livestock and biodiversity at different scales and valuation of market and non-market services. Methodological improvements are required on:

- Extension of the concept of ecosystem services to economic vitality and the well-being of populations.
- Systems borders and services (diversity of beneficiaries, processes, economic and political decision-making, governance structure, etc.)
- Development of appropriate indicators.

[33] This point was expressed as a priority by the EIP-AGRI Focus Group on Precision Farming (2015)

[34] This item was developed in collaboration with Plants for the Future ETP and Food for Life ETP

Expected impacts

- ➢ Better understanding of the aspiration of society with regards to livestock farming,
- ➢ Information tools well designed to fill the gaps between public knowledge and public perception of livestock farming,
- ➢ Better understanding of the drivers of evolution of livestock farming systems and consumption of ASF,
- ➢ Livestock farming systems creating values and addressing societal expectations,
- ➢ Development of circular bioeconomy at local level and emergence of new value chains,
- ➢ Valuing the diversity of livestock production systems,
- ➢ Provision of a diversity of animal-based products adapted to various demands and markets,
- ➢ Increased farm revenues and resilience,
- ➢ Improve working conditions of farmers and employees,
- ➢ Support to a transition towards more sustainable livestock systems and agri-food chains,
- ➢ Public policies and collectives' actions to facilitate transition of the livestock sector,
- ➢ LCA methods suited to system evaluation considering various interactions between livestock, plant, soil and biodiversity and able to cope with local specificities,
- ➢ Methods and tools offering a meaningful baseline against which progress can be measured,
- ➢ Improved participation of farmers, consumers and actors of the food chain in research and transition projects.

5. Cross-cutting issue: the animal as a system

Challenges

The development of more sustainable livestock farming systems renews the scientific priorities of animal research. The animal is at the crossroad of all challenges of the livestock systems. We need to develop the animal's capacities to adapt to a rapidly changing environment and to challenges regarding biological and behavioural traits, to ensure their quality of life and develop a preventive rather than a curative approach to health and welfare management.

The answer to these issues **requires moving from a static vision of the animal** as it has prevailed thus far **to a dynamic vision** considering, in an integrated way, the different phases of development during an animal's lifetime and intergenerational factors, as well as all physiological traits to study the long-term effects of events. This includes the long-term effects of experiences in early phases of life and the ability of animals to compromise and adapt to changing environments during their lifetime. This involves cross-disciplinary approaches (biology, biostatistics and bio-informatics) related to the various functions studied and the different periods of the lifetime. We need to know more about the mechanisms that regulate the dynamics of genome expression during the animal's lifetime, among which microbiome and epigenetics play a role. The non-genetic factors contributing to the transgenerational transmission of traits is a new and important issue. Living organisms should now be considered as holobionts interacting in a shared environment with complex microbial (symbiotic and commensal microbial ecosystems) fluxes. The regulation through animal genetics, early programming mechanisms (epigenetics) that modulate the expression of genotypes and the biological functions and ontogeny of microbiomes interacting with the animal's genome and epigenome should be elucidated. Research will allow the understanding of phenomena, contribute to developing new breeding programmes for more robust and adaptable animals and to developing management practices aimed at controlling the different key animal performances traits. The mechanisms should not only be addressed in animal models because important differences exist between species. Much of this research is pre-competitive and can then be used in different member states to develop their own markets and products.

R&I priorities

R&I priorities may support the production of a variety of more efficient and robust animals, adapted to a variety of dynamic farming conditions.

5.1. Understand the early development of phenotypes to build more robust and adaptable animals

It is now well established that the construction of the individual's phenotype can be influenced at a very early stage of life. Periods to consider range from the properties and the quality of gametes, the periconceptional phase (chromatine organisation and first cells differentiation), the embryo-larval/foetal life (organogenesis), to feto-maternal interactions, the neonatal period until weaning (great upheavals and first apprenticeships for young animal). It is important to study the effect of exposition to different factors (environment, nutrition) in prenatal or postnatal period on the programming of the individual to optimise its performance in adulthood.

The peri-conceptional period (from fertilisation to the first days of embryonic life) constitutes a key stage in the development of the phenotype since a significant remodeling of the chromatin and a massive epigenetic reprogramming of the gamete nuclei will be initiated, the newly formed embryonic genome will begin to express itself and the first cellular differentiations will take place. We need to:

- decipher the interactions between genome and epigenome in the response to environmental variations, as well as the mechanisms of intergenerational transmission by male and female routes in order to be able to use them to drive the phenotype of descendants.

- determine how the embryo perceives its environment, modifies its epigenome and modulates its transcriptome, characterise the mechanism underlying sex-related differences.

The embryo-fetal and embryo-larval life is the period of formation and differentiation of all organs (organogenesis). In mammals, it is a period of finely regulated interactions with the mother during gestation while in non-mammalian species (birds and fish) it is a period of strong interactions between the animal and its environment in a broad sense (biotic and abiotic factors). Environmental stimuli can impact developmental trajectories specific to each organ and each sex. This is why certain time windows will be more or less harmful or beneficial on a particular organ. The major questions are:

- Identify the most determining time window in the development of each function and elucidate the long-term effects in order to determine if it is possible to guide/control adult phenotypes based on long-term effect mechanisms, in particular epigenetic mechanisms.

- Understand the programming role of the placenta in mammals, taking into account differences between sexes.

- Study the cellular composition of organs and tissues in farmed species as it was done in mice using transcriptomic analysis, establish the epigenomes of these cells and analyse the impact of environmental stimuli. The consequence on subsequent fertility is a crucial issue. This may require the development of *in vitro* cellular models (organoids) that mimics the organs of interest.

- Establish criteria to characterise the state of maturity at birth/hatching of young animals (morphological indicators, blood indicators, etc.), in relation to their future potential for survival, development and performance.

The neonatal period until weaning (or first food intake in fish/birds) is a period of major upheavals for the young: sudden change in its environment, exposure to pathogens, establishment of relationship behaviours with the mother, peers and man. The microbiota and development of emotional behaviours have key roles which are largely unknown:

- Understand and control the establishment of different microbiota in farm animals and explore their interactions with the immune system to identify specific sensitive biomarkers and potential therapeutic targets.

- Study the bidirectional "microbiome-intestine-brain" axis in relation to animal health, welfare and behaviour. New approaches have to be developed to study the effects of genetics x nutrition x digestive microbiota on the phenotype expression.

- Elucidate the role of the digestive microbiota in the efficiency of feed use in livestock and the reduction of methanogenesis in ruminants.

- Understand the establishment of socio-emotional behaviours, relationships with humans, cognitive abilities in order to facilitate the co-adaptation of the animal and the breeding environment. This also includes the effects of stress and/or early positive experiences on the neurocognitive development of individuals and their descendants. The effect of early experience on neurobiological development (cerebral organogenesis, neurogenesis, maturation of neuroendocrinological structures) must be elucidated.

5.2. Characterise genetic resources to assess their potential and take advantage of additional diversity

The genetic resources available in Europe represent a heritage that is still largely unknown, particularly in their potential for more sustainable, diversified and resilient systems in the face of health and climatic shocks. It becomes essential to revisit the importance of intra-species genetic diversity. We have *in situ* populations and collections hosted by biological resource centres (e.g. cryobank) with storage initiated before the rise of genomics and an absence of phenotyping on characteristics of interest. The approach at the European level makes it possible to integrate breeds that have had very varied evolutionary histories. Considering adaptation to climate change, European resources may not be enough, and it will be necessary to look for variability elsewhere. This axis covers the following points.

Analyse genomic diversity to prioritise resources to phenotype and to optimise the use of genetic diversity to adapt animals to the diversity of tomorrow's livestock farming systems. It is necessary to complete the genomic characterisation with criteria to identify the best candidates for a phenotyping test (e.g. when a new pathogen appears, having the genomic information to identify particularly genotypes variable or rare for genes or regions of interest).

- Systematise the molecular typing of all genetic resources in the collection, to identify genotypes potentially to be tested.
- Rely on the functional annotation of genomes to improve the coupling between genotype and phenotype, and progress in the prediction of expected phenotypes.

Characterise the phenotypic expression of genetic resources in various environments to better know the functionalities of genetic resources and better use genetic diversity in varied environments, in particular their adaptations capacity and robustness. Here the European scientific infrastructure is important to cover a wide range of possibilities (ESFRI ambition).

- Mobilise stakeholders (farmers, industry, research) and current recording systems to identify environments and geographical zones of interest to test and record genetic resources in contrasted production systems and thus evaluate their potential for the agroecological transition. Using sensors or IoT will allow the recording of new data specifically targeting indicators of resilience and adaptation.
- Characterise and compare available genetic resources in the same environment and conversely evaluate genetic x environment interactions. An important aspect is to consider the consequences of the selection of a trait like productivity on other functions like reproduction, health, behavioural robustness, longevity and adaptation to climate change.
- Develop integrative approaches coupling the genetic and epigenetic variability of the host and that of the microbiota to study phenotypic plasticity.
- A particular attention must be paid to genetic diversity of local breeds (sometimes at risk of extinction) that can supply high-quality and innovative foods, beneficial for human health (e.g. supply nutraceutical foods), for local economies, for increased resilience and particularly suitable to organic systems as well as to alternative species (e.g. donkey, goat, etc.).

Mobilise genetic resources for diverse, resilient and multi-performing livestock systems[35]

- Redesign breeding objectives, for a diversity of environments and production systems. This should include new traits at the individual level (disease resistance, heat tolerance, environmental impacts, etc.) but

[35] This is part of a CSA aiming at structuring the animal and plant genetic community to prepare for future research actions

also traits related to (positive) interactions between individuals for resilience at upper scales and will include understanding and managing interactions between genotype, environment and management.

- Develop novel or refined breeding methods to make the most of genetic diversity (selection methods, cross-breeding, mixtures of populations or of individuals with complementary characteristics and/or developing positive interactions…).
- Develop knowledge on the optimum genetic and phenotypic diversity that can sustain the resilience of the herd, the farm and the territory.
- Reconsider objectives and organisation of animal breeding schemes to bridge the gap between selection on dominant and smaller breeds that may offer advantages to respond to a diversity of system.

5.3. Towards multi-performing animals

Improve the efficiency of feed conversion by livestock remains a priority for farm income, environmental impacts and use of resources. However, the rate of improvement in genetic merit of feed conversion rate is likely to be modest in the future because it sometimes approaches its biological limit (i.e. poultry), practical barriers as environmental issues, use of alternative feed materials and animal welfare issues may constrain future improvements. Research is needed to re-evaluate feed efficiency indicators and testing under these constraints to improve routine trait recording and breeding. Feed efficiency evaluation must encompass classical approaches to consider the entire production cycle of the animal, which therefore includes some robustness characteristics and must be evaluated with the use of alternative feeds which are less in competition with human food but can impair biological efficiency of animal.

- The role of microbiota (notably digestive microbiota) on digestive efficiency should be studied notably when alternative feeds are used.
- Other key determinants of feed efficiency include animal fertility both in dairy and pig, longevity (cows and sows), animal precocity (beef), reduction of mortality *in utero* and before weaning (piglets, calves). In broiler and eggs production, moving towards slower growing birds and the extension of the laying time of animals must be evaluated for efficiency and quality of ASF.

Characterise animal's immunity in its environment. The mechanisms of immunity are directly related to disease resistance and to the vaccine responsiveness. This includes the programming of the immune system of the neonate (immunomics) and its broad consequences on health, the genetic determination of the variability of the immune response and looking for early biomarkers to predict individual phenotypes and the factors influencing the ability of animals to return to a physiological state after a stress. Further research is needed to:

- Evaluate the interaction between feed, the development of immunity and increased resistance of animals to pathogens especially for young animals (piglets, chicken). Applied research may include the prediction of individual immune capacity through integration of immune phenotype and genetic and epigenetic identifies in interaction with rearing practices.
- Model the risk and efficacy of vaccines, revision of vaccine prophylaxis in the light of changes in rearing practices like outdoor farming according to genotype, development of effective vaccines and natural immunostimulant molecules to strengthen the immunity of young animals and the efficacy of vaccines.

Understand the role of microbial communities for animal health. Understanding the functions of the animal's microbial communities and host-microbiota interactions will contribute to an effective control of the balance of the microbial ecosystem for the benefit of animal health and welfare as well as human health (zoonoses, antibiotic resistance) and to develop innovative prophylactic and therapeutic tools and strategies. This requires:

- Study the most resilient/beneficial microbial assemblages at different stages of the animal's life, interrelationships between different animal microbiota (intestine, lungs, skin, reproductive system), and to include beyond microbial fractions (fungi, bacteriophages and viruses). Research has to understand how we can modulate the metabolites and other small molecules produced by a given microbiota (without changing its composition) that has beneficial effects on animal health (on the maturation of intestinal epithelium barrier for instance).

- Understand the role of the implantation of the microbiota in early life on the development of the immune system and its broad consequences for health throughout life.

- Understanding of how we can modulate the metabolites and other small molecules produced by a given microbiota (without changing its composition) and that have beneficial effects on animal health (on the maturation of intestinal epithelium barrier for instance).

- Developing methods to control in farms the composition of these microbial ecosystems (feeding and rearing practices, immunostimulants, pre/pro-biotics, phages, etc.) and evaluate their consequences on other traits for practical purposes.

Understand the relations between animal welfare and animal health. According to the WHO definition, health includes physical and mental health and therefore welfare. It is important to:

- Understand the relationship between animal welfare and health as well as the animal's awareness of its condition and to decipher the mechanisms linking welfare and health.

- Study the effect of stress and positive emotions on health, notably on the immune system and health problems that may arise from adjustments in rearing systems aiming to improve welfare (outdoor access, use of straw bedding, etc.).

- Study the relationship between health, welfare & efficiency and the impacts of stress during various stages of husbandry on resilience should also be considered, as well as the scale of the animal's career in order to understand multifactorial phenomena. Regarding health, research should cover livestock diseases, metabolic disorders and infectious diseases.

Understand the sensory, cognitive and emotional capacities of animals. A better understanding of the animal's awareness of its welfare and health state will help to better manage them, to contribute to the analysis of the effects of enrichments of the living environment and transformation of farming methods. Addressing animal's quality of life requires to:

- Acquire knowledge on the capacities of livestock species to perceive the environment, carry out learning, memorise, interpret information, and interact with their peers and with farmer and decipher the underlying molecular and neurophysiological mechanisms. It is also important to understand the links between cognitive capacities and welfare. To reach the objective, a methodological challenge is the development of brain imaging and the analysis of the data resulting from it.

- Understand how does the animal perceive itself as sick or having a poor welfare, to what extent preclinical behavioural signs of disease exist and can be detected and how this perception establishes itself during development (*in utero*/*in ovo*, from birth to the end of its life) towards behavioural resilience adaptation.

- Investigate from ethological and multi-disciplinary studies the affective states to characterise positive mental states, their behavioural and physiological expression in relation to farming conditions and practices, behavioural robustness and balance between negative and positive states throughout lifespan.

- Consider the construction of animal personality including genetics, epigenetics, pre- and perinatal experience and social transmission in particular to better understand the co-adaptation of animal populations with the practices of farmers.

- A key issue is the development of indicators to characterise the mental states of animals and their behavioural robustness.

5.4. Improving research infrastructures towards innovation

Addressing the challenge and transition to more sustainable livestock farming and food systems will require concerted effort to develop world class Research Infrastructures (RI) bringing together national facilities at the pan-European level in the field of animal genetic resources, phenotyping, and nutrition, animal health and welfare and husbandry practices is still needed as mentioned in the ESFRI Roadmap[36]. At the same time, growing societal concerns about animal welfare are encouraging the Replacement, Reduction and Refinement (3Rs principles) of the way animals are used in research with far less invasive methods that remain to be developed. Precision farming techniques, robotics and digital technologies also enable the collection of many physiological and behavioural parameters at high speed without impairing animal integrity. These innovations will profoundly change the way livestock research is performed and the role of RIs, making networking and harmonisation of methods even more necessary.

Beyond the **AgroServ project[37]**, which already brings together 12 recognised European infrastructures in the animal, plant and food fields which mainly concerns the "One Health" approach, ATF strongly support:

- **The development of a multi-species and multi-disciplinary European research infrastructures** in animal sciences, to support the livestock sector in the agroecological transition and the digitalisation of agriculture. This RI will be focused on the animal as a system, as the central part of future farming systems. It will involve the development of a wide range of methods and tools to increase phenotyping capabilities, both vertically (fine functional exploration of biological functions in small numbers) and horizontally (non-invasive measurements in large numbers) using the most advanced techniques. This would be complementary to the EuroFAANG [38]consortium, supported by FP6 H2020.

- **The development of a research infrastructure dedicated to alternatives to animal experiments**. The development of new cellular models such as 3D cultures and organoids of the tissues of interest and organ-on-chip (multi-channel 3D microfluidic cell culture chips that simulate the activities, mechanics and physiological response of whole organs) are to be developed to limit or replace animal experiments (3R principles) and to break down and model the interactions between organs.

- **The creation of a European "large animal clinic"** where genome edited animals could be genotyped and phenotyped. Large units specialised in one species need to be identified as phenotyping platforms, to be linked to groups that are identified as specialists of a function (immune response, metabolism, reproduction, development). This would require strong networking activity and international collaboration (I3 project).

- **The creation of a virtual infrastructure for developing the concept of digital twins.** This will allow to develop *in silico* experiments to improve knowledge on the mechanisms and processes at different scales, to predict

[36] ESFRI Roadmap, 2020: https://roadmap2021.esfri.eu
[37] https://agroserv.eu/
[38] https://eurofaang.eu/

different outputs by multiplying the experimental situations and to anticipate the emergence of new properties. This particularly concerns animal phenotypes in response to changes in the environment at different time scales and livestock farming systems in response to innovations.

Expected impacts

- More efficient and robust animals adapted to varied farming conditions and that can react quickly to changes (climate and health hazard, feed quality, etc.),
- Improvement of all traits linked to animal health (early survival, longevity, immune competence, vaccine effectiveness, epidemiological parameters, resistance to diseases...),
- Animal able to cope with diversified feed not in competition with human food,
- Integrated animal health and welfare strategies integrating complementary levers (e.g. genetics, nutrition, microbiomes monitoring, husbandry practices, health and welfare management, digital technologies),
- Overall contribution to food security by supporting innovation in breeding and the farming sector,
- Economically, environmentally and ethically robust and sustainable breeding and rearing blueprints for all classes of livestock,
- Deep phenotyping on complex traits,
- High throughput phenotyping in commercial and experimental farms,
- Optimisation of the utilisation of European infrastructures,
- Development of new alternatives to animal experiments,
- Facilitation of knowledge dissemination and implementation,
- Different (epi-)genotypes perfectly suitable for a wide spectrum of production systems.

Appendix 1 – More information about ATF

ATF is a European Public-Private Partnership and a leading body of expertise linking European research providers - including all the major research public centres in Europe - and the private sector for developing innovation in the livestock sector.

We work together to identify actions that are needed to foster knowledge development and innovation for a resource efficient, sustainable, competitive and safe livestock production sector in Europe fostering more sustainable food systems.

We are a knowledge-based organisation working on the forefront of livestock related issues in Europe. Our members are mainly representatives from knowledge providers, industry organisations and farmers organisations. They have expertise in every aspect within the livestock value chain; from feeding and breeding to production and processing. We bring together actors of the European livestock sector to share a common vision and create an integrated approach that is needed to contribute to the environmental and societal challenges our mission involves.

Our goals are to stress the importance of supporting knowledge development and innovation by enhancing cooperation and knowledge exchange; to set the agenda for research and innovation in the animal domain, to promote sustainable livestock production for Europe's future; and to propose science-based solutions to the major challenge of global food security in the context of a limitation and mitigation of global warming, restoration of biodiversity and efficient resource use.

ATF members and engaged partners

Public research providers	Aarhus University	Denmark
	Agroscope	Switzerland
	BIOS Science Austria	Austria
	Biotechnical Faculty, University of Ljubljana	Slovenia
	CIEL	United Kingdom
	CRA-W	Belgium
	CREA -	Italy
	Cyprus University of Technology	Cyprus
	DAFA	Germany
	FINS – Institute of Food Technology	Serbia
	INIA-CSIC	Spain
	INIAV	Portugal
	INRAE	France
	Institute of Animal Science	Czech Republic
	LUKE	Finland

	NMBU	Norway
	Polish Academy of Sciences	Poland
	Swedish University of Agricultural Sciences	Sweden
	Teagasc	Ireland
	WUR	The Netherlands
Industry representative organisations	AnimalhealthEurope	
	FABRE-TP	
	FEFAC	
	FEFANA	
Farmer innovation group	ECIP	

ATF observers

Special Observer	EAAP - European Federation of Animal Science
Observers	European Commission - Directorate-General for Research & Innovation
	European Commission - Directorate-General for Agriculture & Rural development
	GASL-FAO: Global Agenda for Sustainable Livestock
	GRA GHG - Global Research Alliance on Agricultural Greenhouse Gases
	ICAR - International Committee for Animal Recording
	SCAR ANIHWA Animal Health and Welfare
	SCAR CWG Sustainable Animal Production

Stakeholders met from 2021 to 2023

This document was developed by the ATF Presidency and Secretariat in consultation with ATF members in 2022 and 2023. Some topics were developed in collaboration with European Technology Platforms (ETPs) notably, Plants for the Future[39], TP Organics, Food for Life.

This document was also inspired by the strategic approach to EU agricultural Research & innovation (European Commission), ATF participation in the FACCE-JPI[40] stakeholder and HDHL-JPI[41] events, SCAR groups (Sustainable Animal Production; Animal Health and Welfare, Bioeconomy, Agroecology, Food Systems, Foresight Task Force), exchanges of views with EC DGs (namely DG AGRI, DG RTD, DG ENVI,

[39] ATF-Plants for the Future Position Paper, September 2019. ATF-Plants for the Future Policy Brief, May 2020.
[40] https://www.faccejpi.net/en/faccejpi.htm
[41] https://www.healthydietforhealthylife.eu/

DG CLIMA, DG CONNECT, DG SANTE), European Parliament members and FAO representatives. A large range of European and national state stakeholders were also consulted (see table 1) from industry, farmers organisations, branch or value chain organisations, NGOs, think tanks, international organisations, etc.

European Commission	Cabinet of Vice-President Frans Timmermans / Maroš Šefčovič (European Green Deal)
	DG AGRI
	DG CLIMA
	DG CONNECT
	DG ENVI
	DG FISMA
	DG RTD
	DG SANTE
	EU Mission Board for soil health and food
European Parliament	MEP Álvaro Amaro (Portugal)
	MEP Chris MacManus (Ireland)
	MEP Colm Markey (Ireland)
	MEP Herbert Dorfmann (Italy)
	MEP Irène Tolleret (France)
	MEP Jérémy Decerle (France)
	MEP Jytte Guteland (Sweden)
	MEP Marlene Mortler (Germany)
	MEP Pietro Fiocchi (Italy)
	MEP Tom Vandenkendelaere
European Technology Platforms	EATiP - European Aquaculture Technology and innovation Platform
	Food for Life
	Plants for the Future
	TP Organics
Farmers	CEJA - European Committee of Young Farmers
	COPA COGECA
Industry	AnimalhealthEurope
	CLITRAVI - The Liaison Centre for the Meat Processing Industry in the European Union
	EDA - European Dairy Association
	EFPRA - European animal by-product processing sector

	FEFAC - European Feed Manufacturers' Federation
	FEFANA - EU Association of Specialty Feed Ingredients and their Mixtures
	FIL-IDF - International Dairy Federation
	Global Dairy Platform
	INTERBEV
	UECBV - European Livestock and Meat Trades Union
International organisations	BEUC – The European Consumer Organisation
	EAAP - European Federation of Animal Science
	FAO - Food and Agriculture Organisation of the United Nations
	GASL - Global Agenda for Sustainable Livestock
	ICAR - International Committee for Animal Recording
	United Nations Food Systems Summit 2021
NGOs	Compassion in World Farming
	EEB – European Environmental Bureau
	ELO – European Landowners' Organisation
	IEEP – Institute for European Environmental Policy
	WWF
Research	Audencia Business School
	Dublin Declaration (Vrije Universiteit Brussel - University of Medicine and Health Science)
	ICA - Association for European Life Science Universities
Think Tanks	EABA - European Algae Biomass Association
	ERBS - European Roundtable for Beef Sustainability
	Eurogroup for Animals
	Farm Europe
	FVE – Federation of Veterinarians of Europe
	SAI Platform
	UEVH - Union of European Veterinary Hygienists

Appendix 2 – Fit with on-going or past HorizonEurope and Horizon2020 projects

Below are listed for reference some major Horizon (2020 and Europe) funded projects related to the key R&I areas suggested in this document.

Project short name	Project title	Website	ATF SRIA 2024 SD related to each project
AE4EU	Agroecology for sustainable agricultural and food systems	www.ae4eu.eu	SD4: 4.1, 4.3
ALFA	Scaling up the market uptake of Renewable Energy Systems by unlocking the biogas potential of Agriculture and Livestock Farming	https://alfa-res.eu/	SD1: 1.1, 1.2, 1.3 SD4: 4.3, 4.4
ALL-Ready	The European Agroecology Living Lab and Research Infrastructure Network: Preparation phase	www.all-ready-project.eu	SD1: 1.1, 1.2, 1.3, 1.4 SD5: 5.4
AVANT	Alternatives to Veterinary ANTimicrobials	https://avant-project.eu/	SD2: 2.2, 2.3, 2.4
BioSecure	Enhanced and cost-effective biosecurity in livestock production	https://biosecure.eu/	SD2: 2.2, 2.3, 2.4 SD3: 3.2 SD5: 5.3
BovReg	Identification of functionally active genomic features relevant to phenotypic diversity and plasticity in cattle	https://bovreg.eu/	SD2: 2.4 SD5: 5.2, 5.2, 5.3
Circular Agronomics	Efficient Carbon, Nitrogen and Phosphorus cycling in the European Agri-food System and related up- and down-stream processes to mitigate emissions	https://cordis.europa.eu/project/id/773649	SD1: 1.2, 1.3
ClearFarm	Co-designed Welfare Monitoring Platform for Pig and Dairy Cattle	www.clearfarm.eu	SD1: 1.1 SD2: 2.1, 2.2 SD5: 5.4
Code Re-farm	Consumer-driven demands to reframe farming systems	https://coderefarm.eu/wp-coderefarm/	SD1: 1.1, 1.2 SD2: 2.2, 2.4 SD3: 3.1, 3.2, 3.3 SD4: 4.2, 4.3, 4.4 SD5: 5.3
COMBAT	COntrolling and progressively Minimizing the Burden of Animal Trypanosomosis	www.combat-project.eu	SD2: 2.2, 2.3, 2.4 SD5: 5.3

Project short name	Project title	Website	ATF SRIA 2024 SD related to each project
CryoStore	Innovation in germplasm cryopreservation for improved animal breeding and the conservation of Europe's livestock biodiversity	https://cordis.europa.eu/project/id/101120454	SD5: 5.1, 5.2, 5.3, 5.4
DEFEND	Addressing the dual emerging threats of African Swine Fever and Lumpy Skin Disease in Europe	https://defend2020.eu/	SD2: 2.3, 2.4 SD3: 3.3 SD5: 5.3
FERTIMANURE	Innovative nutrient recovery from secondary sources – Production of high-added value FERTIlisers from animal MANURE	www.fertimanure.eu	SD1: 1.2, 1.3 SD4: 4.1, 4.2
GEroNIMO	Genome and Epigenome eNabled breedIng in Monogastrics	www.geronimo-h2020.eu	SD2: 2.2, 2.3, 2.4 SD4: 4.4 SD5: 5.1, 5.2
HealthyLivestock	Tackling Antimicrobial Resistance through improved livestock Health and Welfare	https://healthylivestock.net/the-project/	SD2: 2.3, 2.4 SD3: 3.2
HEARTLAND	Health, Environment, Agriculture, Rural development: Training network for LAND management	https://cordis.europa.eu/project/id/814030	SD1: 1.1, 1.2, 1.3, 1.4 SD2: 2.2, 2.4 SD3: 3.1, 3.2, 3.3 SD4: 4.1, 4.2, 4.3, 4.4 SD5: 5.3
ICRAD	International Coordination of Research on infectious Animal Diseases	https://www.icrad.eu/	SD2: 2.2, 2.3, 2.4
INTAQT	INnovative Tools for Assessment and Authentication of chicken meat, beef and dairy products' QualiTies	https://h2020-intaqt.eu/about/	SD2: 2.4 SD3: 3.2, 3.3 SD4: 4.3, 4.4
MonoGutHealth	Training and research for sustainable solutions to support and sustain gut health and reduce losses in monogastric livestock	https://cordis.europa.eu/project/id/955374	SD2: 2.3, 2.2, 2.4 SD5: 5.4
NanoFEED	Nanostructured carriers for improved cattle feed	https://cordis.europa.eu/project/id/778098	SD2: 2.4, 2.2 SD5: 5.3, 5.4
NANOSTIMULANTS	Biostimulants nanoencapsulation to increase yield under drought stress	https://isoplexis.uma.pt/projeto-biostimulants/	SD1: 1.2
NOMAD	Novel Organic recovery using Mobile ADvanced technology	www.projectnomad.eu	SD1: 1.2, 1.3, 1.4
Nutri2Cycle	Transition towards a more carbon and nutrient efficient agriculture in Europe	www.nutri2cycle.eu	SD2: 2.3, 2.4

Project short name	Project title	Website	ATF SRIA 2024 SD related to each project
PATHWAYS	Pathways for transitions to sustainability in livestock husbandry and food systems	https://pathways-project.com	SD1: 1.1, 1.2, 1.3 SD2: 2.2, 2.4 SD3: 3.1, 3.2, 3.3 SD4: 4.1, 4.2, 4.3, 4.4 SD5: 5.3
PIGWEB	An infrastructure for experimental research for sustainable pig production	www.pigweb.eu	SD5: 5.4
PPILOW	Poultry and PIg Low-input and Organic production systems' Welfare	https://ppilow.eu/	SD1: 1.1, 1.2, 1.3 SD2: 2.1, 2.2, 2.4
PREPARE4VBD	A Cross-Disciplinary Alliance to Identify, PREdict and prePARe for Emerging Vector-Borne Diseases	https://prepare4vbd.eu/	SD2: 2.2, 2.3, 2.4 SD5: 5.3
Re-Livestock	Facilitating Innovations for Resilient Livestock Farming Systems	https://re-livestock.eu/	SD1: 1.1, 1.2, 1.3 SD2: 2.2, 2.4 SD3: 3.1, 3.2, 3.3 SD4: 4.1, 4.2, 4.3, 4.4
RES4LIVE	Energy Smart Livestock Farming towards Zero Fossil Fuel Consumption	https://res4live.eu/	SD1: 1.1, 1.2
ROADMAP	Rethinking Of Antimicrobial Decision-systems in the Management of Animal Production	www.roadmap-h2020.eu	SD2: 2.3, 2.4 SD4: 4.4
RUMIC	Prebiotic Functional Enhancement of Rumen Microbiomes	https://cordis.europa.eu/project/id/840804	SD2: 2.2, 2.3, 2.4 SD5: 5.3
RUMIGEN	Towards improvement of ruminant breeding through genomic and epigenomic approaches	https://rumigen.eu/	SD2: 2.2, 2.3, 2.4 SD5: 5.1, 5.2, 5.3
SeaWeedWorm	Discovering how bioactive compounds from seaweed kill parasitic worms	https://cordis.europa.eu/project/id/101064872	SD2: 2.3, 2.4 SD5: 5.3
SmaRT	Small Ruminant Technology - Precision Livestock Farming and Digital Technology for Small Ruminants	https://smartplatform.network/	SD1: 1.1, 1.2 SD2: 2.4 SD4: 4.4 SD5: 5.3
SMARTER	SMAll RuminanTs breeding for Efficiency and Resilience	https://cordis.europa.eu/project/id/772787	SD5: 5.1, 5.2, 5.3
STEP UP	Sustainable Livestock systems Transition and Evidence Platform for Upgrading Policies	https://horizon-stepup.eu	SD1: 1.1, 1.2 SD2: 2.4 SD3: 3.1 SD4: 4.1, 4.2, 4.3, 4.4 SD5: 5.3

Project short name	Project title	Website	ATF SRIA 2024 SD related to each project
SustainSAHEL	Synergistic use and protection of natural resources for rural livelihoods through systematic integration of crops, shrubs and livestock in the Sahel	www.sustainsahel.net	SD1: 1.1, 1.2, 1.4 SD2: 2.4 SD4: 4.2, 4.4 SD5: 5.3
TechCare	Integrating innovative TECHnologies along the value Chain to improve small ruminant welfARE management	https://techcare-project.eu/	SD2: 2.2, 2.2, 2.3 SD5: 5.3
The BoS	The Body Societal: Unfolding Genomics Infrastructure in Cattle Livestock Selection and Reproduction	https://cordis.europa.eu/project/id/949577	SD2: 2.3, 2.4 SD5: 5.1, 5.2, 5.3
TOXOSHEEP	Study of the molecular mechanisms underlying Toxoplasma-induced early abortions in a pregnant sheep model of infection	https://cordis.europa.eu/project/id/101028616	SD2: 2.3, 2.4 SD5: 5.1, 5.4
Treat2ReUse	Treatment of Animal Waste to Reduce Gaseous Emissions and Promote Nutrient Reuse	https://cordis.europa.eu/project/id/795974	SD1: 1.1, 1.2, 1.3, 1.4
VetBioNet	Veterinary Biocontained facility Network for excellence in animal infectiology research and experimentation	https://vetbionet.eu/	SD4: 4.1, 4.2, 4.3, 4.4 SD3: 3.3 SD5: 5.4

Layout: Susana De Magalhaes / Animal Task Force -Institut de l'Elevage

Publishing Director: Frank O'Mara / Animal Task Force & Teagasc

ISBN n° 978-2-7148-0308-5 / IE n°0024 603 005

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