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TOWARDS IMPROVEMENT OF RUMINANT BREEDING THROUGH GENOMIC AND EPIGENOMIC APPROACHES

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H2020 – Research and Innovation Action

Deliverable 2.2

Fictional Futures: Scenarios on future breeding

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1 Summary

Objectives:

The deliverable D2.2 provides a set of fictional scenarios on future breeding for task 2.3 of Rumigen, which serve as point of comparison in the participatory citizen consultation of T2.4 and contribute to the development of the ex-post "room of acceptance". While the scenarios represent realistic (although speculative) future technological pathways, they are fictional in nature as they are intended to explore the wide range of potential future implications of the application of technologies that are studied in RUMIGEN, including the extreme ends of this range. This is done to better understand citizen perception of this large range of implications.

Teams involved:

The RUMIGEN partners and other contributors that have worked on this Deliverable are:

- Eliance (ALLICE)
- DBT: Danish Board of Technology – Fonden Teknologiradet
- WU: Wageningen University
- WR: Stiching Wageningen Research
- EFFAB: European Forum of Farm Animal Breeders

The scenarios proposed in this task have been constructed by taking into account the multidimensionality of European livestock farming and keeping in mind the dimensions of the ex-ante “room of acceptance”. The aim of these scenarios is to assess, together with citizens, the acceptability of the different dimensions in order to determine the ex-post 'room of acceptance. The scenarios are therefore highly contrasting and fictional in order to better assess the impact of the choices that can be made. The four scenarios are named:

- Full throttle towards livestock 2.0
- Parsimonious breeding
- Status quo
- Livestock: a social contract

There is no single scenario that would meet expectations. The objective remains to test the social acceptability of the various dimensions and to define possible directions for a desirable future for European livestock farming, which will maintain its diversity, at least on the basis of the diversity of territories and their agronomic potential. For each scenario, aspects related to:

1) the multidimensionality of the livestock farming through the areas of markets, employment and labour, inputs, environment and climate, and certain social and cultural issues,
2) the changes in society through demographics, diets and sustainability
3) Climate change and Livestock
4) Breeding technologies: valuable tools to meet these challenges

have been taken into account as much as possible, with the aim of highlighting the trade-offs that will be necessary in the coming decades to establish policies that will foster the development of a livestock sector that contributes to sustainability at the global level.

2 Objectives of the T2.3 in Rumigen

In the context of climate change and transition towards more sustainable farming systems, efficient, sustainable and socially acceptable breeding goals and programs, innovative genomic prediction methods and precision management tools are needed to produce robust cattle that efficiently manage the trade-offs between production and adaptation to extreme climate conditions (heat stress, reduced feed qualities and quantities, and disease pressures). In this context, sustainable breeding could be defined as the selection of healthy animals that fit better into the local environment, are able to cope with environmental changes, produce high quality products combined with a low environmental footprint and provide sufficient incomes to farmers, without compromising the ability of future generations to meet their own needs and selection objectives.

Therefore, RUMIGEN aims to deliver breeding programs with an improved sustainability for both cosmopolitan and local breeds in a diversity of environmental conditions, taking into account trade-offs between breeding objectives, preservation of genetic diversity and available technologies (including innovations developed in the course of the project). It will also lead to the development of new management indexes for precision farming combining genomic, phenotypic and epigenetic information. This aim will be achieved through dedicated scientific activities, as well as a multi-actors-driven approach, taking into account societal acceptance, feasibility and overall resource and economic efficiency.

Task 2.3 stipulated that 4-5 scenarios on realistic futures with the use of new breeding approaches would be produced. The scenarios was planned to combine possible technological strategies, so that each of them represent a possible implementation of breeding approaches inside/outside the “room of acceptance”. These would serve as background information for the citizen consultations in T2.4, in order to provide concrete reference points for the citizens’ discussions and feedback on the “room of acceptance”. The multi-actors enrolled in T2.1 have taken part in co-creating the scenarios, so that these reflect possible future “societal contracts”, as the stakeholders see these. The scenarios feature various possible approaches to the use of distinct technologies, but more broadly different scenarios for European cattle farming and the likely impact of this choices on the scale of the farm, but also on society as a whole, in particular on the availability and consumption of products (dairy and meat).

The deliverable D2.2 provides a set of fictional scenarios on future breeding for task 2.3 of Rumigen, which serve as point of comparison in the participatory citizen consultation of T2.4 and contribute to the development of the ex-post "room of acceptance". While the scenarios represent realistic (although speculative) future technological pathways, they are fictional in nature as they are intended to explore the wide range of potential future implications of the application of technologies that are studied in RUMIGEN, including the extreme ends of this range. This is done to better understand citizen perception of this large range of implications.

The purpose of these encounters is multiple: to refine and provide further data for T2.2 and develop the final ex-post room of acceptance, to provide a rough outline and feel for the borders between the possible and the desired, to provide an early risks analysis connected to the scenarios, which can inform WPs 3-8, and finally to provide a sounding board for a subsequent socio-economic ‘reality check’ of the scenarios in light of research and data provided in WPs 3-7.

3 Context

The European Union is the world's leading agricultural power. In 2019, the continent's agricultural output will be worth around €418 billion. The Common Agricultural Policy (CAP), introduced in 1962, was a response to the need to increase food production in a Europe devastated by years of war by modernising production tools. The quest for competitiveness, risk management and the evolution of agricultural policies have strongly influenced the structure of supply chains and production strategies in Europe. For example, since the end of the Second World War, European livestock farms have expanded by increasing their capital (mechanisation, livestock, land), while still relying predominantly on family labour, which has significantly increased productivity. In the agricultural sector, the substitution of capital for labour has generally been accompanied by the productive specialisation of farms, allowing them to better exploit economies of scale in the production of a single product by making the best use of equipment, supplies and specific skills for that production (Dong et al., 2016). In animal production (as in crop production), genetic selection has brought significant advances to farmers since the early 1970s, not only to increase productivity and ensure animal fertility and health, but also to reduce resource use and environmental impact.

In 2006, the FAO report 'Livestock's Long Shadow' (Steinfeld et al.), which initially identified livestock as a major contributor to climate change through its greenhouse gas emissions, estimated at 18%, later revised to 14.5% in 2013 (Gerber et al., 2013), prompted significant reflection on the role of animal production. With three-quarters of these greenhouse gas emissions attributed to herbivores and livestock occupying an estimated 70-75% of global agricultural land (across all sectors) (Foley et al., 2011; Van Zanten et al., 2016), this debate cannot be ignored. In Europe, one-third of the Agricultural Utilised Area (AUA) is permanent grassland, of which one-third is moorland and pasture that is only viable for ruminants. However, these ruminants also consume 15% of the cereals produced in Europe (FAOSTAT) and a significant amount of oilseeds and protein crops, 70% of which are imported.

The increasing global demand for animal products (especially in emerging countries), public health recommendations on animal protein consumption, animal welfare advocacy and growing interest in vegetarianism all raise questions about the sustainability of the current system. In addition, the promotion of the beneficial effects of reducing meat consumption in the diet, together with technological innovations such as in vitro meat and the consumption of insect protein, raise questions about the role of animal products in the diet of the future. At the European level, production needs will also evolve in line with demographic changes and a likely shift in dietary preferences towards 'healthier' trends with a focus on reducing carbon footprints.

The debates about livestock and food resonate with wider societal issues about our development model and its responsibility for the damage done to our planet. Redefining production methods aims to maintain production while managing environmental impacts. Precision agriculture uses sensors, robots and statistical data to guide and adjust technical interventions, while agroecology seeks to redesign agricultural systems based on the use of ecosystem services. These options are emerging in a context of recurring tensions in European markets for animal products, where challenges are not only the result of economic uncertainty, but also part of a transition from a 'productivist' model to more resource-efficient ones.

In the coming years, the context of European livestock production will inevitably change to address the impact of climate change on livestock and the forage and cereals available to feed them. Beyond agricultural production, climate change has cascading effects on food security, global trade and the environment. The impacts are manifold and in many respects uncertain, especially given the fluid geopolitical context. Contributions to global food security from different regions of the world may change, and regional agricultural policies and trade strategies may be significantly altered, with far-reaching implications for overall orientations.

In this contextual section, we will first provide an overview of the different dimensions that define livestock, including economic, social and environmental aspects. As the primary purpose of livestock is to produce food, we will then focus specifically on societal aspects such as demographics, changing dietary patterns and sustainability. Rumigen is a programme that addresses the challenge of "producing robust and efficient livestock that can manage the trade-offs between production and adaptation to extreme climate conditions". Therefore, we will also look at the challenges associated with climate change and mitigation, and the potential of breeding technologies to address this challenge.

3.1 The multidimensionality of European livestock farming: Between impacts and services

The impacts and services associated with ruminant livestock in Europe are numerous and form the background to the scenarios to be proposed. To make them clearer, they are presented in context.

The term 'services' refers to the benefits that society derives from livestock activities and/or the use of animal products. The study of both the positive and negative impacts of livestock is generally based on multi-criteria assessments. Life cycle assessment (LCA) approaches are often chosen because they provide a basis for large-scale standardised assessments. The advantage of LCA is that it assesses multiple types of impacts and all stages of the life cycle simultaneously. However, economic, social and cultural dimensions are often insufficiently considered in environmental analyses. Results may differ depending on the scale considered: for example, an increase in animal productivity may result in resource savings at animal level (less food consumed due to lower production requirements), but to increase resource requirements at the farm level (more animals to compensate for lower production per animal) and even more at the regional level. The choice of functional unit, the basis for quantifying performance indicators, can change the assessment of the magnitude of certain impacts. Expressing emissions per 'kilogram of product' or 'hectare utilised' can change the relative ranking of livestock systems. The choice of functional unit depends on whether the objectives are global or local and short or long term.

The variety of impacts and services is presented in five main areas: markets, employment and labour, inputs, environment and climate, and certain social and cultural issues.

3.1.1 Markets

Food consumption: Accounting for almost 60% of daily protein intake, average European consumption of animal products ranges from 59 to 114 g/day for adults (EFSA, 2012), while WHO recommendations range from 50 to 70 g/day (WHO, 2007). Since the 1990s, animal protein consumption in Europe has remained relatively stable, with substitution between products. Two social phenomena seem to characterise the evolution of European dietary patterns: i) a certain "de-animalisation" of meat consumption, leading to a substitution of red meats (-14% between 2000 and 2013) by white meats (especially poultry) and an increasing prevalence of processed products that hide the reference to the animal; ii) the development of quality labelled foods, demonstrating the attraction of Europeans for products with heritage or even gastronomic value. This reflects a growing appreciation of higher quality production methods.

Production: At the level of the European Union, animal production accounts for about 45% of the value of final agricultural production. Europe is the world's largest producer of dairy products, accounting for 20% of total production, and the third largest producer of beef, after the United States and Brazil (12% of world production). About one third of livestock is concentrated in certain regions

(Denmark, the Netherlands, northern Germany, western France), particularly in dairy, pig and poultry production. On average, a 'European livestock holding' uses 34 hectares of agricultural land and maintains a herd of 47 livestock units, with considerable variation between farming systems and countries, with newer Member States generally having smaller farms.

International trade: Trade flows of animal products between EU Member States are substantial and have increased over the last decade. Global demand for animal products, driven by demographic changes and economic development in emerging economies, is boosting EU exports, particularly in the dairy and pigmeat sectors. The trade balance for cattle will be 1.7 million euros and for dairy products 17.9 million euros in 2022 (accounting for 30% of the agricultural trade surplus) (Comext Eurostat, April 2023, [https://agriculture.ec.europa.eu/system/files/2023-05/agrifood-extra-eu27_en.pdf]). Competition on the European and international markets is fierce.

Downstream sectors: European industries in the animal products sectors (dairy, meat, animal feed) generated revenues of around €400 billion in 2013. Despite the large number of companies, the food industry within this sector is dominated by a few large global companies. In 2012, large retailers accounted for 54% of food sales, with the remainder distributed through other channels (markets, butchers, restaurants, etc.).

3.1.2 Employment and labour

Direct and indirect employment: European livestock farms employ approximately 4 million people (both salaried and non-salaried), with 80% of these jobs in Member States that joined the EU after 2004. However, this number continues to decline due to the ageing of the farming population and productivity gains (Charroin et al., 2012). Mixed crop-livestock and dairy farms account for the majority of jobs (37% and 25% respectively). The animal product industries employ more than one million salaried workers in the EU. The employment multiplier effect is estimated to be between 1.2 and 2.5, depending on the sector, and is generally higher in the meat sectors than in the dairy sectors. Some regions are highly dependent on the downstream sectors due to their importance in the local economy.

Labour: On average, a livestock farm employs 1 to 2 workers. Family labour continues to decline in favour of wage labour, agricultural service companies and new collective agreements (Purseigle and Hervieu, 2022). Salaried employees account for 15% of the EU's livestock labour force, with significant variations (from 2% in Belgium to 50% in Denmark). The attractiveness of the farming profession appears to be low, with working conditions and lack of recognition contributing to the disengagement of younger generations (Battaglini et al., 2014; Bernues et al., 2011).

Relation to techniques: Animal husbandry practices are evolving rapidly. Technical choices affect the duration of work, justifying research efforts into simplified farming practices such as feeding, milking schedules and synchronisation of animal physiological cycles. These choices change the relationship farmers have with their work and their animals. Some may opt for grazing systems to improve their working conditions (Brummel and Nelson, 2014), while others prefer zero grazing (Meul et al., 2012). The increase in labour productivity tends to limit the emotional attachment to animals and change the symbolism and rules of the occupation (Dufour, 2009). The benefits of technologies for economic productivity are also debated. Some argue that they are at worst neutral in terms of labour productivity (e.g. self-service feeding), while others believe that they reduce working time but also income (e.g. the use of milking robots (Kvapilik et al., 2015)).

Precision livestock farming, which is defined by the use of automation and sensors to manage animal husbandry, primarily emphasises the time saved by new technologies. However, the introduction of automation and digitisation brings with it new tasks related to equipment management, maintenance and data analysis (Schewe and Stuart, 2015). These tasks may offset the time saved by eliminating the actual labour. In this case, the gain is mainly associated with a reduction in mental workload.

Occupational health: This issue is generally under-researched. The agri-food industry, including slaughterhouses, has a high incidence of illnesses due to repetitive tasks, standing postures, noise and low temperatures. In the livestock sector, even if physically demanding work has decreased, musculoskeletal disorders are still very important and mental stress due to strain has increased, particularly in the context of ever-increasing administrative pressures. It is impossible for a breeder to take time off work to seek medical treatment, and many of them give up on treatment or jeopardise their chances. At best, the breeder can try to find staff to cover the needs of daily work. Along with cancer and cardiovascular disease, suicide is now a major cause of mortality among farmers worldwide (Kolstrup et al., 2013).

3.1.3 Inputs and mobilised resources

Inputs refer to the direct and indirect resources used in livestock production, including crops, land, water, fertilisers and energy. These inputs have become a key aspect of environmental efficiency and are the subject of debate:

- The territorial footprint of livestock production due to the relatively low (and variable depending on the physiological stage) conversion rate of plant proteins to animal proteins. This competition with the production of proteins directly consumed by humans is a food security issue. However, animal proteins generally have a higher nutritional value and contain essential nutrients (amino acids, vitamins, trace elements and minerals) (Lebret and Picard, 2015).
- The relocation of protein sourcing and its impact on and dependence of the EU on these external areas outside Europe,
- The pressure on biodiversity.

Animal feed: European livestock farms consume 220 million tonnes of cereals and oilseeds per year, half of which is in the form of industrial concentrates rich in protein and energy, while the other half consists of cereals consumed on the farm and produced on the farm. The EU imports 70% of its oilseed protein (mainly soya) for animal feed, of which one third is for ruminants, mainly dairy cows. If the protein contained in all concentrated feeds is taken into account, the EU's protein dependence decreases to 40% and further decreases if the protein contained in coarse forage, grass and other cereals produced on the farm is included.
European soy consumption, as one of the main protein source for animal feeding, is very controversial (deforestation, processing, storage and transport, etc.). The production of soybean increased by 8.4 times in 50 years and is very concentrated. Five countries produced almost 90% of the soybean in the world. In 2018, USA represented 35.5% of the worldwide production (123.7 millions of tons), Brazil 33.8% (117.9 Millions of tons), Argentina=10.8% (37.8 Millions of tons), China=4.1% (14.2 millions of tons), India=4.0% (13.8 millions of tons). The 5 largest consumers are China with 29.5% of the worldwide consumption (103.7 millions of tons), USA with 17.3% (60.8 millions of tons), Argentina with 14,7% (51.7 millions of tons), Brazil with 13.2% (46.4 millions of tons) and EU with 5.0% (17.6 millions of tons) [https://tradehub.earth/wp-content/uploads/2020/10/Global-Soybean-Trade-The-Geopolitcs-of-a-Bean-1.pdf].

Land use: While herbivorous livestock require more land than monogastrics, they can use pastures and rangelands on land unsuitable for crops, which has minimal competition with the production of biomass for human consumption. In the EU, there are approximately 74 million hectares of permanent pasture (including 17 million hectares of rangeland and moorland), which can only be used by ruminants, 10 million hectares of temporary pasture and 35 million hectares of fodder crops, of which a quarter is used by ruminants. Therefore, for grasslands, ruminants are efficient in converting them into protein (Peyraud and Peeters, 2016).

Energy: Livestock production consumes about 45% of the energy used in agriculture (28 Mtep/year in the EU). The energy required to produce one kilogram of protein varies according to the type of product (beef: 177 to 213 MJ/kg; milk: 37 to 144 MJ/kg (De Vries and De Boer, 2010)). Depending on the type of feed, indirect energy (production of industrial feed and fertilisers) can account for between 50% and 80% of the total energy, so improving food self-sufficiency is a way to save energy. Livestock farming also produces energy through the methanisation of its waste, but the development of this sector varies from country to country. Germany produces two thirds of Europe's biogas in almost 9,000 farms, while France, despite developing this sector with almost 2,000 production units, recovers less than one fifth of its waste by methanisation (FranceAgriMer, 2022 https://www.franceagrimer.fr/content/download/69402/document/20221007_RESSOURCES_EN_BIOMASSE_ET_METHANISATION_2022_WEB-V2.pdf). In addition, in certain regions, there may be competition between the biomass needs of methanisation and animal feed, creating tensions (by-products of the agri-food industry such as sugar beet pulp, residues of major crops such as straw for feed or bedding, or some cover crops, and even crops such as maize for silage).

Water: As water is very unevenly distributed geographically, its consumption per unit of product is a relevant indicator only in a specific context. Methods for assessing water use take into account different types of water (blue water withdrawn for irrigation of livestock or fodder crops, green water stored in soils) and use different indicators (consumption levels, use efficiency, water stress). As a result, the results vary considerably and are difficult to compare. Depending on the source, between 27 and 53,200 litres of a combination of blue and green water can be mobilised to produce one kilogram of beef.

The use of blue water can be reduced by favouring non-irrigated (or less irrigated) crops for livestock feed and by encouraging ruminant grazing. Some studies recommend modifying the physiology of animals, such as increasing their growth rate or reducing their feed consumption ratio. However, considering physiological or behavioural modifications in the name of environmental benefits raises ethical concerns.

3.1.4 Environnement & climate

Greenhouse Gas Emissions (GHG): As a significant contributor to anthropogenic GHG emissions, livestock production has a clear negative impact on climate change. In the EU, about 42% of livestock emissions are attributed to feed, 22% to enteric fermentation, 19% to livestock effluents and 17% to direct and indirect energy consumption (livestock and related industries). Due to enteric fermentation, ruminants are responsible for almost 60% of greenhouse gas emissions from livestock in Europe, equally divided between the meat and dairy sectors. Conversely, grazing systems allow sustainable carbon sequestration in the soil of permanent pastures, which has a positive impact on the climate.

The intensity of emissions varies considerably within the same type of production, especially for ruminants, reflecting differences in soil and climatic conditions, farming practices and supply chain management. This variability is particularly pronounced for ruminant meat production, while it is less pronounced for bovine dairy production (Figure 1), although the carbon footprint remains significant compared to plant protein sources. According to Grossi et al. (2019), the implementation of mitigation strategies aimed at reducing emissions from the livestock sector is needed to limit the environmental burden of food production while ensuring sufficient food supply for a growing global population. Mitigation can be achieved directly by reducing the amount of greenhouse gases emitted, or indirectly by improving production efficiency.

Reducing direct greenhouse gas emissions is relatively well documented. At the animal level, one approach is to optimise diets to limit excess nitrogen excretion. Nitrous oxide (N2O) emissions come directly from manure and mineral nitrogen fertilisers. For methane emissions, which are physiologically linked to the rumination of herbivores, there are prospects for reduction through the use of feed additives (such as 3-nitro-oxypropanol, which inhibits the final synthesis of methane by archaea (Yu et al., 2021)), dietary optimisation and genetic selection of animals with lower emissions (Fresco et al., 2023).

Soil carbon reserves are not permanent, but result from a dynamic balance between organic matter input and mineralisation. Carbon is readily degraded at the surface but stable in deeper layers (Beniston et al., 2014; Follett et al., 2005). Once stored in the deep soil of an ecosystem (permanent pasture, crop, forest), carbon can persist for centuries if there is no change in land use or vegetation. In the case of livestock farming, therefore, the maintenance of soil carbon stocks depends in particular on the maintenance of permanent pastures used extensively (less than 1.2 UGB/ha). Typical bocage landscapes in livestock regions and silvopastoral systems also act as "carbon sinks" (Pellerin et al., 2013; Walter et al., 2003). In temperate zones, permanent pasture soils store about

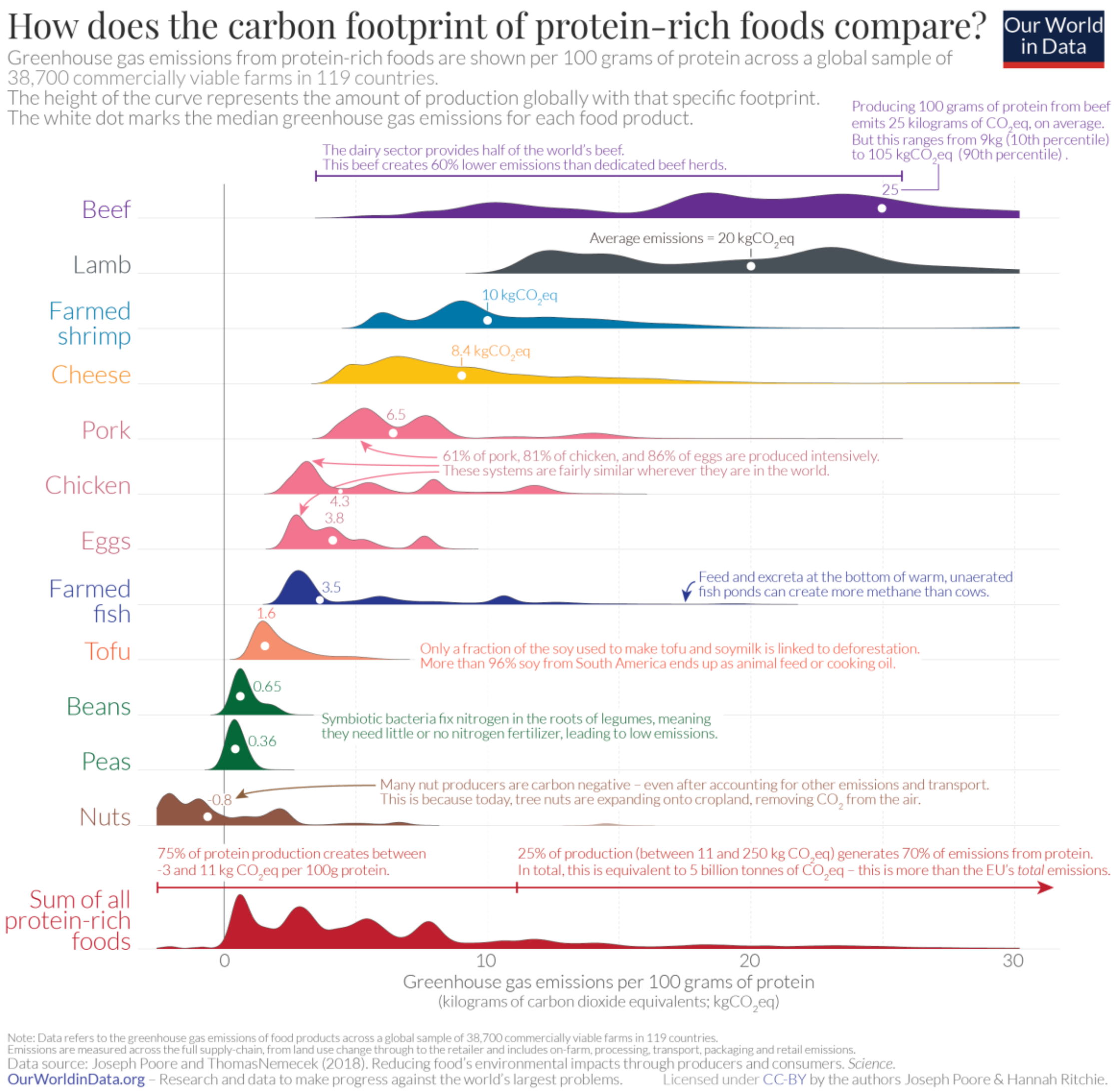

Figure 1. Estimated global variation in GHG emissions of 12 foods, per 100 grams of protein (Hannah Ritchie, 2020 from Poore & Nemecek, 2018)

60-70 t C/ha (Angers et al., 2011; Soussana et al., 2004), with a maximum organic matter content of 2.5% in the soil, resulting in a storage capacity of around 1.5 tons of carbons over 50 years. Beyond this point, the carbon storage capacity of permanent pastures becomes saturated. This storage capacity can be increased with leguminous grasslands compared to grass-only pastures (Lüscher et al., 2014).

Theoretically, this soil sequestration could offset the greenhouse gas emissions from human activities (Balesdent and Arrouays, 1999). Terrestrial soils contain 1,500 to 2,400 billion tonnes of carbon in the top ten centimetres (about three times more carbon than in plant biomass and the atmosphere). An annual increase in carbon stocks of 4‰ could potentially offset annual global greenhouse gas emissions. On the contrary, the conversion of permanent pasture into arable land is the main driver of soil carbon loss in Europe. This loss is happening much faster than carbon storage.

Air quality: Livestock is the main emitter of ammonia (90%), which is a precursor of fine particles. These particles are a major public health concern as they cause respiratory diseases and inflammation.

Soil: Livestock affect the biological and physical functioning of soils by providing organic matter and nutrients that improve soil fertility. However, livestock also introduces biological, pharmaceutical and chemical contaminants. The effects of livestock farming vary according to whether the land is used for crops or pasture. The most positive impacts are associated with permanent pasture, especially those with low stocking rates (less than 1.2 UGB/ha), while high animal densities have the most negative impacts.

Water quality: In areas with high livestock densities, increased nitrogen and phosphorus in water contribute to eutrophication of water bodies (lakes, rivers and coastal areas). This leads to deteriorating water quality and higher costs for wastewater treatment. The EU has focused on monitoring and reducing nutrient loads from wastewater (Nitrates Directive). The load per hectare is the main aggravating factor, but the impact depends on the sensitivity of the receiving environment.

Biodiversity: The positive impact of livestock farming on wild biodiversity is achieved through the maintenance of permanent pastures, meadows and heaths, which are rich in floral and faunal biodiversity and would naturally develop into woodland in the absence of livestock farming. Biodiversity in agricultural landscapes increases with livestock farming due to the presence of (even temporary) pastures, crop diversification and bocage and silvopastoral landscapes. However, the decline of permanent pasture and increased use of fertilisers has reduced the plant diversity used for livestock production. Nevertheless, experimental trials demonstrate the positive effects of forage species mixtures, particularly in terms of livestock production (intakes and nutritional quality) and resilience to climatic events.

The indigenous biodiversity of livestock species has been greatly reduced. Today, a few specialised breeds dominate, characterised by large populations and extensive ranges. Their narrow genetic base limits their potential for adaptation, especially in the case of dairy cattle. However, incentive programmes for the promotion and conservation of regional breeds have made it possible to maintain the diversity of cattle breeds. Genetic diversity is a key component of the ability to adapt to changing livestock conditions: resistance (or tolerance) to disease and the effects of climate change, as well as potentially less direct human presence or less rich diets. The genetic capabilities of so-called rustic breeds are a precious and valued resource because they are linked to the natural constraints of particular environments.

3.1.5 Social and Cultural Issues

Animal health issues: 60% of emerging human infectious diseases are zoonotic. The last decade has seen an increase in the circulation of infectious agents (avian influenza, bluetongue, etc.), highlighting the increasing globalisation of health risks. Recent years have been marked by the spread of numerous infectious agents of animal origin, such as H1N1 and H5N1 influenza, bluetongue, chikungunya, Ebola, West Nile, coronavirus, epizootic haemorrhagic disease, etc. International institutions (WHO, OIE, FAO) have recognised the significance of this trend and are now prioritising a comprehensive and preventive approach to safeguarding human and animal health, known as 'One World-One Health'. This approach emphasises the importance of the human-animal-ecosystem interface in the emergence and evolution of pathogens.

The impact of zoonoses is felt in the health, economic, environmental and social spheres. Animal diseases are responsible for 20% of global production losses. Zoonoses often lead to production losses in animals without clear clinical signs. Economically, for many diseases, the sale and movement of live animals depends on the 'disease-free' status of farms, regions or countries. The investment made to eradicate tuberculosis illustrates the economic stakes associated with this status.

The risks are different for free-range or pasture-based livestock and for confined livestock. In the former case, the 'neighbourhood' risks between farms are well documented for TB and represent a significant contamination risk. In the latter case, it is the amplification of phenomena that is of concern. For example, the outbreak of Q fever in the dairy goat sector in the Netherlands between 2007 and 2010 was extreme. Large herds of only 300 farms in a densely populated area released very high concentrations of Coxiella burnetii pseudospores into the air. This resulted in the largest Q fever epidemic ever documented, with 4,107 reported human cases (Morroy et al., 2015).

Since 2010, numerous reports (WHO, World Bank, etc.) have highlighted the health and economic threat of antibiotic resistance associated with the use of antibiotics in livestock. This use clearly falls under the 'One Health' framework, as the challenges of acquired resistance shared by bacteria affect both humans and animals, with the spread of resistance being global due to intense international trade and transport. The misuse of antibiotics contributes to amplifying and accelerating the selection and spread of resistance. In 2006, the European Commission banned the use of antibiotics as growth-promoting feed additives. This practice had been used in industrial livestock farming since 1940 and is still used in some countries, such as the United States.

The problem of antibiotic resistance also affects the environment. The commensal bacterial flora and the environmental bacterial flora are often referred to as the focus of antibiotic-related risks (Aarestrup, 2015). Exposure of environmental bacteria to antibiotics from different sources can promote the emergence and selection of resistance.

In livestock, between 30 and 90% of the antibiotics administered to animals are excreted without being metabolised. Therefore, livestock effluents may contain still-active antibiotics that continue to exert selection pressure on effluent or soil bacteria through the application of manure. However, this phenomenon needs to be qualified and quantified. Finally, many biological agents (pathogenic micro-organisms, viruses, parasites) and chemical substances (synthetic hormones) present in wastewater are potential contaminants. Storage of manure does not significantly reduce the presence of pathogens. In contrast, composting, thermophilic anaerobic digestion (methanisation) and liming are effective treatments to reduce the potential load of pathogens.

Animal welfare: Since 1974, when the first EU legislation on animal welfare was adopted, animal welfare requirements have evolved based on sound scientific knowledge, improving the quality of animals' lives in accordance with citizens' expectations and market demands. In 2009, the Lisbon treaty included an explicit recognition that animals are sentient beings and that the EU and its

Member States bear an ethical responsibility to prevent maltreatment, pain and suffering. The European Union has one of the most comprehensive set of rules in the world on animal welfare, covering farm animals at the farm, during transport and at when slaughtered. This legislation is one of the most advanced in the world.

These rules reflect the five freedoms contained in the Council of Europe's Convention for the Protection of Animals kept for Farming Purposes:

- Freedom from hunger and thirst (by ready access to fresh water and diet to maintain health and vigour).
- Freedom from discomfort (by providing an appropriate environment including shelter and a comfortable resting area).
- Freedom from pain, injury or disease (by prevention or rapid diagnosis and treatment).
- Freedom to express normal behaviour (by providing sufficient space, proper facilities and company of the animal's own kind).
- Freedom from fear and distress (by ensuring conditions and treatment which avoid mental suffering).

While the first three freedoms aim to protect the animal's bodily integrity, the meaning of the last two is entirely different because the aim is to guarantee a quality of life for the animal. An examination of various pieces of national legislation on the protection of animals shows that while various provisions prohibit physical harm to animals, very few take into account concern for its welfare. Indeed, very few European lawmakers have passed laws that recognise and protect the five freedoms.

Animal welfare is at the heart of sustainability, as a good level of animal welfare is linked to less antibiotic use, healthier animals entering the food chain and reduced transmission of diseases from animals to people. Animal welfare is an essential element of the 'Farm to fork' strategy, adopted by the European Commission in May 2020 in the context of the European Green Deal. Within its framework, the Commission will revise the animal welfare legislation to align it with the latest scientific evidence, broaden its scope, make it easier to enforce and ultimately ensure a higher level of animal welfare. The Commission will also consider options for animal welfare labelling to better transmit value through the food chain, because farming practices vary widely and 'best practice' is often not recognised by labels, although some countries have developed them (e.g. the UK and the Netherlands). However, animal welfare is better respected in quality label production than in other forms of agriculture.

The leading position of the EU animal welfare legislation in the world is an asset in the long term but importation of cheaper products from third countries with sometimes lower animal welfare standards could jeopardize the progress made by EU producers as well as mislead EU consumers. In addition, EU producers have to compete at global level and consumers outside the EU are not necessarily aware of the high animal welfare standards of EU products. Defending and reinforcing European positions in international organisations such as the World Organisation for Animal Health (OIE) are a priority, to develop international standards on animal welfare.

Cultural and heritage issues: French, Italian, Dutch, Balkan cheeses, charcuterie and dried meat techniques are abundant in Europe... Official designations of origin and quality (PDOs and PGIs) illustrate the richness of the food heritage linked to animal products. Their number is increasing and exceed 800 in 2022. However, the transmission of artisanal know-how is not entirely guaranteed. Pastoral livestock farming contributes to the creation of cultural landscapes that act as identity markers and attract a largely urban European society.

3.2 Changes in society: demographics, diets and sustainability

Demand for agricultural commodities for human consumption is driven by diet and population dynamics. Although our focus is on European agriculture, in such a globalised world it is difficult to ignore the consequences of changes on a global scale, particularly for animal products exported to third world countries. Many populations in sub-Saharan Africa and South Asia could benefit from increased consumption of animal-based foods through improved nutrient intake and reduced malnutrition (Beal et al., 2023).

Depending on the assumptions made about the evolution of dietary patterns, global needs will differ and may be more or less met and balanced. In the first scenario, as proposed by FAO, so-called "trend" diets would continue past trends, maintaining current diets in developed countries and the ongoing dietary transition in developing countries. Daily calorie requirements would not be met globally, with sub-Saharan Africa in particular remaining well below recommended levels in 2050. In the second scenario, reflecting 'healthy' diets, consumption shifts towards diets more in line with nutritional recommendations. In this case, diets in different regions of the world tend to converge. This option alone would enable sub-Saharan Africa to overcome its nutritional deficiencies. A global shift to 'healthy' diets would reduce total calorie intake and meat consumption in developed countries. This reduction could reduce the need for arable land in European regions and allow strategies to be developed for the agricultural use of the land freed up.

Demographics remain the key driver of food demand. In Europe, where the population is expected to decline, food demand would stagnate for "trend" diets or decline for "healthy" diets. In Africa, however, demand would soar regardless of diet type, increasing the need for arable land and even dependence on imports, especially where land availability is limited, as in North Africa and the Middle East.

While producers are an important part of the solution, their ability to reduce environmental impacts is limited. These limitations can result in one product having a higher impact than another that is nutritionally equivalent.

Poore and Nemecek (2018) estimate that the environmental impacts of animal products can significantly exceed those of plant-based alternatives (Figure 1). For example, meat, aquaculture, eggs and dairy products use about 83% of the world's agricultural land and contribute 56 to 58% of various food emissions, despite providing only 37% of our protein and 18% of our calories. Can animal products be produced with sufficiently low impacts to redress this significant imbalance? Or will reducing consumption have greater co-benefits for environmental sustainability, for example by reducing high impact products, processed meat and moderate red meat and saturated fat to reduce disease risk?

According to them, consumers can play an important role in avoiding high impact producers. Communicating average product impacts to consumers enables dietary change. They consider a scenario in which consumption of each animal product is halved by replacing above-average GHG-emitting production with plant-based alternatives. While dietary change is feasible for any individual, achieving widespread behavioural change will be challenging in the narrow time frame remaining to limit global warming and prevent further irreversible biodiversity loss. By communicating the impact of products, they can trigger many small changes in large numbers of consumers.

When produced at an appropriate scale and in accordance with local ecosystems and contexts, animal-based foods can play an important role in circular and diverse agro-ecosystems. In some circumstances, they can help restore biodiversity and degraded land, and mitigate greenhouse gas emissions from food production (Beal et al., 2023).

3.3 Climate change & Livestock

In the proposal, it is written "the main goal of RUMIGEN is to produce robust and efficient cattle able to manage the trade-offs between production and adaptation to extreme climate conditions (heat stress, reduced feed qualities and quantities, and disease pressures). RUMIGEN considers sustainable breeding as the selection of healthy animals able to cope with environmental changes, producing high quality products with low environmental footprint, while providing sufficient incomes to farmers, without compromising the ability of future generations to meet their own needs and selection objectives."

Adaptation of ruminants to climate change is indeed a major challenge for the coming years, as it will require adaptability on several fronts. Several studies have been carried out on the impact of climate change on agriculture and animal production at European or global level. In particular, a series of simulations have been carried out using the GlobAgri-AE2050 model developed by INRAE and CIRAD. These simulations assess production capacity, arable and grassland requirements and imports and exports in 2050 for each of the 21 world regions analysed. They take into account the impact of climate change on agricultural production and the availability of arable land. Developments in agricultural techniques - including input use, genetic improvement, technological innovation, etc. - and their impact on yield trends have also been considered.

It is now widely accepted that the growing concern about the thermal comfort of livestock is justified not only for countries in tropical zones, but also for countries in temperate zones where high ambient temperatures are becoming an issue. Even if at the European level we can assume that the decline in cattle herds will continue, at the global level animal production will have to increase in the coming decades to meet the growing demand for food from animal source.

In the second half of the 20th century, the livestock sector focused on improving productivity, modifying the environment and improving nutrition, rather than on improving stress resistance. This approach dramatically increased the productivity of livestock, but also increased their sensitivity (reduced their thermal plasticity) to hot environments. The processes by which livestock respond to changes in their environment are critical for survival, but often have a negative impact on the productivity and profitability of livestock systems. Collier et al (2019) describe the importance of acclimation, acclimatisation and adaptation to environmental stressors, with a focus on heat stress. Acclimation and acclimatisation are coordinated phenotypic responses to environmental stressors, and the response decays when the stressors are removed. If chronic stress persists over several generations, the acclimatisation response becomes genetically 'fixed' and the animal is adapted to the environment. Improving knowledge of the genetic differences between adapted animals will provide useful information on the genes associated with acclimation. This information will be useful in identifying genes associated with improved thermotolerance.

Climate change will affect livestock and livestock systems, in particular through its effects on (i) animal productivity, health and well-being, and (ii) the quantity, quality and type of feed resources, animals and thus ultimately the digestibility of these resources, not to mention the availability of water resources for drinking. Furthermore, climate change may also affect livestock systems as part of their adaptation process, including the choice of better adapted livestock practices, including the selection of species and breeds that are better adapted to average and extreme manifestations of climate change, but may be less productive.

3.3.1 Effects of climate change on animals, their productivity, health and well-being

The increased frequency of extreme temperatures induced by climate change is expected to increase the number of periods during which ruminants are outside their comfort zone, with potentially negative consequences for meat and milk production, as well as for animal health and welfare, if no corrective measures are taken (Figure 2: Rojas-Downing et al., 2017). Outside this so-called thermal neutrality zone, animals are under stress, which they try to counteract through behavioural changes (increased movement, seeking shelter, etc.) and/or physiological responses (changes in respiration, ingestion, etc.).

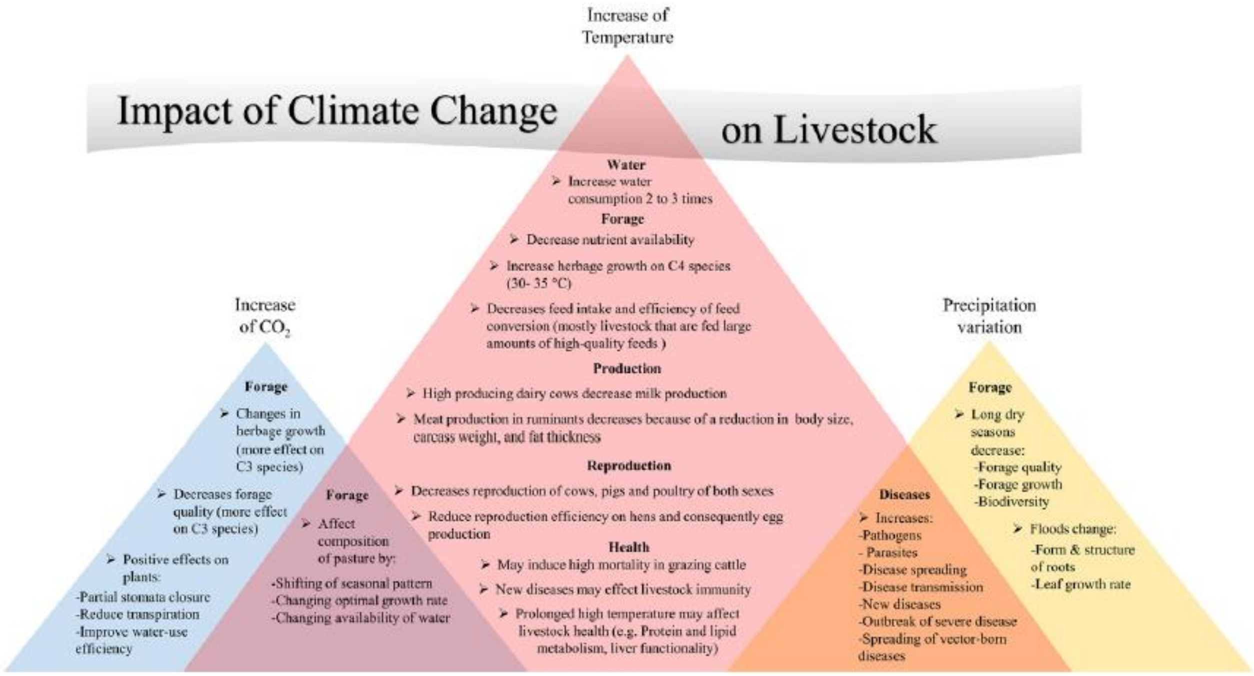

*Figure 2. Impact of climate change on Livestock (from Rojas-Downing et al., 2017)**

Production

Heat stress has a negative impact on milk and meat production. In addition to quantity, the quality of animal products is strongly and negatively affected by a hot environment. In the case of milk, heat stress has a more significant impact on high quality products, such as cheeses with protected designations of origin from many European countries, which have a worldwide reputation for excellence. Summer et al. (2019) point to the negative effects of heat stress on milk composition (organic and inorganic components), and describe how these changes are strongly associated with changes in cheese-making properties and the market value of milk. These changes have significant negative economic implications for producers and consumers.

Beef cattle, with their lower metabolic rate and body heat production, are generally considered to be less sensitive to heat stress than dairy cattle. However, beef cattle also compensate for increased body temperature through homeostatic mechanisms (panting, sweating and urinating) and behavioural changes such as reduced activity, increased water intake and reduced feed intake. These effects generally result in reduced growth rate and reduced fertility in both males and females.

Key and Sneeringer (2014) show that heat stress would lead to a decrease in milk production in the United States by 2030, ranging from 0.60% to 1.35%, depending on the climate model used (however, the decrease in production would be more than 2% in some southern US states). The authors conclude that it is likely to be more costly (in terms of milk litres lost) to react to annual or intra-annual variations in heat stress than to anticipate it in the long term through adaptation investments, which are not necessarily very expensive as they mainly involve building modifications.

Reproduction

Wolfenson and Roth (2019) describe how hot summer conditions disrupt several reproductive processes, resulting in a significant reduction in conception rates in dairy cows worldwide. When body temperature reaches 39.5°C, reproductive processes can be severely impaired, including disruption of oocyte developmental competence, attenuated embryonic growth and early embryonic death due to impaired hormone secretion, altered ovarian follicular growth dynamics, suboptimal corpus luteum development and attenuated uterine endometrial responses. Effective cooling is essential and a prerequisite for minimising heat stress. However, reducing heat stress during the summer may not be sufficient to maintain reproductive function after the stressor has ended. It is suggested that cooling may need to be combined with other treatments to improve fertility, including treatments to improve ovulation timing, removal of impaired follicles, induction of ovulation in healthy follicles, embryo transfer and progesterone supplementation before and after AI may be required to improve fertility in heat stressed dairy cows.

Diseases

Climate change has also been shown to have had and will have an impact on livestock diseases (Purse et al., 2005; Wilson and Mellor, 2008; Kenyon et al., 2009), and its acceleration is expected to increase this impact (Fox et al., 2011; Fox et al., 2015). This is due to the dual evolution of pathogens through the expansion of their biotopes and the epidemics that future climatic conditions may favour.

Several climate parameters, including humidity and temperature, can influence the survival and development of pathogens, affecting their spatial distribution, parasite and disease intensities, and seasonal infection profiles (Fox et al., 2011). Climate change will not affect all pathogens in the same way. Vector-borne pathogens (e.g. bluetongue virus) appear to be particularly vulnerable. Another example is the current epizootic haemorrhagic disease (EHD), which has been present in Europe since the end of 2022 but is gradually spreading (Spain, Sardinia, Sicily, Portugal, France) and is transmitted by blood-sucking midges of the genus Culicoides, probably transported by winds from the Maghreb. Even small changes in climate can increase the risk of infection by certain pathogens (e.g. the risk of infection of ruminants during grazing by nematodes, Rose et al., 2015).

Health and well-being

The negative impacts of climate change on livestock health and well-being will result from a combination of changes in air temperature (outdoor and indoor), precipitation, and the frequency and amplitude of extreme events (Lacetera, 2019). The direct impacts are mainly due to increased temperatures, frequency and intensity of heat waves. These environmental conditions can disrupt animal health by causing metabolic disorders, oxidative stress, and immunosuppression, leading to infection and death. These effects will be less severe to the extent that adaptation measures are taken to limit the consequences.

3.3.2 Impacts of climate change on feed resources

In addition to drinking water, climate change may also affect animal production through feed, both in terms of available resources (quantitative impact) and their composition, which will affect the digestibility of animal rations (qualitative impact). Available resources include concentrated feeds such as cereals and oilseeds, but more importantly forages, whether cultivated or not, which account for a significant proportion of all agricultural land, including permanent grassland. These resources, which are required in significant quantities in ruminant production, are typically produced on the farm and local climatic conditions have a direct impact on production systems.

A north-south gradient in Europe could affect the availability of feed and its distribution throughout the year. This could potentially lead to higher production in spring but lower production in summer for European latitudes. Climate change may also have a potential impact on the nutritional value of plants consumed by animals, and consequently on the digestibility of proposed rations.

3.3.3 Possible adaptations for cattle to climate change

Gaughan et al. (2019) address an important issue, that of determining the best strategies for adaptation. Adaptation in animals depends on several interrelated factors. All factors that can either increase or decrease adaptability need to be considered. It is well known that selecting animals for high production has increased their susceptibility to environmental challenges. On the other hand, the use of lower yielding cows may reduce heat stress, but reduced production efficiency may lead to increased greenhouse gas emissions. Although a single stressor may be significant, the cumulative effects of multiple stressors (in addition to heat stress) may be significant and need to be considered. Adaptation strategies include adjustments to production systems and genetic improvement for thermotolerance. In addition to adaptation, mitigation strategies should also be considered. These strategies include changes in animal management systems (nutritional interventions, manipulation of the rumen ecosystem, provision of shade, housing, fans and sprinklers). Multidisciplinary approaches involving animal breeding, nutrition, housing and health are needed to reduce the adverse effects of climate change on livestock and to limit the impact of livestock on climate change.

The question of trade-offs in adapting dairy cattle to heat stress is addressed in WP3 of Rumigen. The possibility of genetically selecting livestock for thermotolerance would be a cost-effective tool to achieve a permanent change in an animal's heat tolerance, although the implementation of selection strategies is challenging due to the complexity of the heat stress response and the antagonism between heat tolerance and productivity (Carabaño et al., 2019). To effectively select animals, it is necessary to find phenotypic measures that accurately identify heat-tolerant animals and can be used under field conditions at low cost. In addition, methods need to be developed to efficiently combine knowledge from all 'omics' technologies to generate genetic indices for selecting the best breeding stock. Genetic improvement for heat-tolerant livestock will be effective depending on the production system. Systems with sufficient resources to ensure high animal productivity will benefit more from incorporating heat tolerance into breeding programmes for breeds already selected for high production. In contrast, production systems with limited resources and a challenging parasite environment will benefit more from crossbreeding local livestock with highly specialised, productive breeds.

3.4 Breeding technologies: valuable tools to meet these challenges

3.4.1 Artificial insemination (AI) and Semen technologies

Artificial insemination

AI is a widely used reproductive technique in animal breeding that offers numerous advantages for improving genetic traits and overall herd management and performances, and its use was developed in Europe in the 1950s. It can be performed by a qualified technician, veterinarian or farmer. It involves the controlled introduction of sperm from carefully selected males into the reproductive tracts of females. It has become an indispensable tool in animal breeding, contributing significantly to genetic improvement, disease control and the overall sustainability of livestock production. It allows the use of genetically superior sires without the limitations of natural mating, which leads to the propagation of desirable traits but results in lower conception rates. By facilitating the use of a wider range of sires, AI can play a crucial role in maintaining and increasing genetic variability and can be considered an efficient use of genetic resources.

Sexed semen

Sexed semen technologies enable the sorting or separation of sperm cells based on their sex, allowing for the production of semen with a predetermined sex ratio. These technologies have significant implications for animal breeding and herd management. The main technology used in bovine reproduction for sex-sorting sperm is flow Cytometry, which involves staining sperm cells with a fluorescent dye that binds to the DNA. As the stained cells pass through a flow cytometer, they are sorted based on their fluorescence, which is related to the amount of DNA in the cell (Sharpe and Evans, 2009). This technology becomes more and more use. In North America, the market of sex-sorted semen, which started around 2006, is estimate to be 30% of the total AI market in 2020, mainly in dairy markets (Seidel and DeJarnette, 2022)

Benefits of sexed semen technologies in bovines are multiple: 1/ It allows for more precise control of the sex ratio in offspring, enabling farmers to tailor their breeding programs to meet specific goals (increase the number of females to expand herd / increase meat production with use of male semen) ; 2/ facilitates the rapid dissemination of genetics from high-performing animals (replacement female needs) accelerating genetic progress and for dairy herd, the identification of a population of dairy cows from which replacements are not desired, leading to a tremendous increase in use of beef semen in dairy herds… In Ireland, the use of sexed semen is highlighted to reduce the number os surplus male dairy calves (Balzani et al., 2021).

While sexed semen technologies offer many advantages, it is essential to note that the accuracy of sex sorting is not 100%, and fertility rates can be lower compared to conventional semen (around 80%).

3.4.1 Oestrus synchronization

Oestrus synchronization in bovine reproduction is a management practice employed to coordinate and control the timing of the estrous (heat) cycle in a group of female cattle. The goal is to induce a large proportion of the females within a herd to express estrus simultaneously or within a defined time frame by the use of one of existing protocols, typically involving GnRH (Gonadotropin-Releasing Hormon) and prostaglandin. This synchronization is often used in conjunction with artificial insemination (AI) or Embryo Transfer to improve reproductive efficiency and overall herd management. For instance, it enables to limit the calving season and facilitates the management of calf health, reduces labor demands…

3.4.2 Embryo technologies

Embryo Production

<u>A - In Vivo Embryo production: Multiple Ovulation and Embryo Transfer (MOET)</u> is an assisted reproductive technique that involves inducing multiple ovulations in a female animal, fertilising them by artificial insemination, harvesting the resulting embryos and transferring them to recipient surrogate dams, requiring hormonal treatments and synchronisation protocols, with an interval between MOET of 1.5-2 months. MOET is of great interest in cattle breeding due to its potential to accelerate the spread of desirable traits, increase reproductive efficiency, and improve the genetic potential of livestock by increasing the influence of elite sires and dams, ultimately leading to faster

genetic progress (Diskin and Kenny, 2016). In addition, MOET has been instrumental in conserving genetic diversity within cattle populations, particularly in rare and endangered breeds.

B- In Vitro Embryo Production: Ovocyte Pick Up In Vitro Fertilization (OPU-IVF) is a technique developed in the late 1980s and commercialised in the 1990s. OPU has revolutionised cattle breeding by providing a practical means of collecting and preserving genetic material from a wide range of animals, regardless of age or reproductive status. It enables the propagation of elite genetics, accelerates the genetic progress of herds and contributes to the conservation of rare and valuable breeds.

It consists of four stages: 1/ Oocyte collection by OPU (Ovum Pick Up), which is a follicular puncture trough the vaginal wall and under ultrasound control; 2/ In vitro oocyte maturation for about 1 day (IVM); 3/ In vitro fertilisation for about 1 day (IVF) and 4/ In vitro embryo development for 7 days (IVD).

It makes it possible to multiply the offspring of genetically valuable females in a limited period of time. In fact, follicular puncture can be performed at any stage of the donor's cycle, every week, without any adverse effects on the donor (van Wagtendonk-de Leeuw 2006). OPU-IVF can be performed on:

- Prepubertal females (from 2 to 3 months of age) using laparoscopic OPU (under endoscopic control) (Currin et al., 2017).
- Pubescent females, heifers or cows, pregnant cows (as long as the ovaries remain accessible - approximately 3 months of gestation) or those with uterine pathologies and up to a few hours after death, using transvaginal OPU under echographic control

In prepubescent females, the interest is to reduce the generation interval. Another advantage of in vitro techniques is the possibility of using semen from several bulls to fertilise oocytes from the same collection, maximising genetic gain and minimising inbreeding. Access to very early embryonic stages allows embryo biopsies to be taken for sexing (Galli et al. 2001) or to evaluate their genetic value without altering the pregnancy rate (de Sousa et al. 2017). Compared to in vivo embryo production, OPU-IVF does not necessarily require superovulation and allows, in theory, the production of more embryos (high variability from one team to another). However, the quality of in vitro produced embryos is lower than those of in vivo derived embryos leading to lower pregnancy rates even if significant progresses have been made last years.Moreover; it is more technically demanding and costly (qualified laboratory staff and equipment). Since 2016, the number of bovine embryos produced in vitro is higher (more than 75% - Viana, 2022 - Stats IETS: https://www.iets.org/Portals/0/Documents/Public/Committees/DRC/IETS_Data_Retrieval_Report_2021.pdf) than the number of embryos produced in vivo, especially in the Americas, which is not the case in Europe (only 25%).

In IVF, oocytes are fertilized by sperm outside the female reproductive tract. Sexed semen can be used in combination with IVF, allowing for the selection and implantation of embryos of the desired sex.

Genome Editing technology

Genome editing is a powerful biotechnological tool that offers unprecedented precision and opportunities for genetic improvement. This technology, primarily based on CRISPR-Cas9 and other genome editing platforms, allows targeted DNA modification of specific genes in an animal's genome. The implications for cattle breeding are immense, ranging from accelerated genetic progress and disease resistance to improved environmental adaptability.

Cattle are susceptible to a number of infectious diseases. Genome editing offers a promising way to improve disease resistance by modifying key immune-related genes. Mueller and Van Eenennaam (2022) review the potential to introduce genetic changes that confer disease resistance or improve welfare. For example, Henning et al. (2021) generate deletions in horn loci to have polled cattle. Other authors report increased resistance to mastitis. This helps to improve animal welfare, improve cattle health and limit the use of drugs and antibiotics.

Efficient reproduction is fundamental to livestock production. Genome editing can be used to address reproductive challenges such as infertility by targeting genes involved in reproductive processes. This not only increases the efficiency of cattle breeding programmes, but also contributes to sustainability by reducing the number of non-productive animals.

Climate change and environmental challenges require livestock breeds that can thrive in diverse conditions. Genome editing offers the potential to modify genes associated with environmental adaptability. For example, Rodriguez-Villamil et al. (2021) discuss the modification of a single gene in the prolactin receptor (PRLR) to confer the SLICK phenotype in Angus cattle, improving heat stress regulation and enabling cattle to better cope with rising global temperatures.

Despite the immense potential of genome editing, ethical considerations cannot be overlooked: there are potential risks associated with the use of these techniques that are currently poorly assessed (off-target, de novo mutation rates). Legislation is not uniform throughout the world. The United States, Canada, Brazil, Australia and China allow the use of genome editing, at least under certain conditions, while Europe does not. This is problematic because the mutations induced by genome editing are precise and could have occurred naturally. Unfortunately, there are no techniques that can identify a genome-edited animal. In a market where semen is traded globally, regulatory differences are complex.

Induced pluripotent stem cells

The use of induced pluripotent stem cells (iPSCs) for in vitro breeding in cattle is an emerging and highly innovative field with the potential to revolutionise genetic improvement and reproductive technologies. iPSCs are reprogrammed somatic cells that can differentiate into various cell types, including gametes (Kobayashi et al, 2017), offering numerous possibilities for cattle breeding until the management of breeding schemes totally in vitro (without the need to access to animals) to reach the “perfect” genotype. While this technology is still in its early stages, this system can rapidly achieve 30–40 times more genetic gain by significantly shortening the generation interval and increasing selection intensity (Hou and al., 2018).

3.4.3 Genomic selection

Genomic selection is a revolutionary approach to cattle breeding that has transformed the industry's ability to make informed breeding decisions based on an animal's genetic potential. This method, based on advances in genomics and bioinformatics, allows the selection of superior breeding candidates even before they reach maturity. It represents a paradigm shift, offering a more precise and efficient means of improving traits such as milk production, meat quality and disease resistance. By analysing an animal's DNA for 10k to 800k single nucleotide polymorphisms (SNPs) along the genome, and based on correlations between SNPs and specific traits estimated in a reference population, it is possible to predict an individual's genetic potential early in life, even at the embryonic stage.

Genomic selection accelerates genetic progress by allowing breeders to identify elite animals at a younger age, shortening the generation interval, extending the number of selected traits and increasing selection for desirable traits (Hayes et al., 2009). This results in more efficient and effective breeding programmes. It can be applied to a range of traits including milk production, meat quality, fertility and disease resistance. However, selection remains limited, notably when several complex traits are targeted simultaneously, due to physiological trade-offs. In addition, genomic selection requires large reference populations, which are hard to reach with local breeds, increasing the economical gap between them and cosmopolitan breeds, thus endangering their preservation.

Genomic selection can be an efficient tool to manage inbreeding and maintain genetic diversity within the population. Genomic selection can be used to maximise genetic advance, but it can also be used to limit consanguinity, avoid genetic load and preserve rare alleles. It is a powerful tool, very efficient, which can give the best and the worst. Within breeds, genomic selection may increase inbreeding rates as shown in Holstein breed (van Kaam et al., 2023) and reduce genetic diversity. Vigilance is therefore required !

3.4.4 Epigenetic

Epigenomics, a rapidly evolving field of genetics, has gained prominence in cattle breeding for its potential to unravel the intricate regulatory mechanisms that influence an animal's phenotype. Unlike traditional genomics, which focuses on DNA sequences, epigenomics delves into the chemical modifications and molecular processes that govern gene expression without altering the underlying DNA sequence. DNA methylation is one of the most studied epigenetic modifications. It involves the addition of methyl groups to specific cytosine bases in the DNA molecule.

Current genetic markers and methods used for Genomic Selection explain only part of the expected heritable fraction of complex traits and diseases. Epigenetic variation has been suggested as one of the explanations for this phenomenon (Ibeagha-Awemu & Zhao 2015; Slatkin 2009). Accumulating evidence suggests that the sperm epigenome may be dynamically modified as a response to environmental stress and may influence fertility (Boissonnas et al. 2013), embryonic development (Liu WM, et al 2012, Yuan S et al, 2016) as well as the progeny phenotype (Schagdarsurengin et al, 2016; Champroux et al, 2018, Skinner et al, 2018 ; Klastrup et al, 2019).

Epigenomics may help refining genomic prediction since it can be artificially modulated to fully express the genetic potential. In Rumigen, The EpiChip underconstruction (WP6) should help answer this question. It will be used to i) explore to what extent the sperm epigenome may influence bull fertility and progeny, ii) decipher the underlying mechanisms of intergenerational epigenetic inheritance and iii) evaluate to what extent epigenetic biomarkers can explain part of the complex traits and may be useful to improve genomic prediction, and study the impact of heat stress.

In the WP7, studies that will help to design practices in cattle in order to modulate favourable epigenotypes are planned. They aim at establishing the relationship between the epigenome and relevant phenotypes under different conditions in cattle to be able to modulate these environmental factors externally for better future performance. The Rumigen WP7 will give some elements on how environmental conditions can shape the epigenome in foetuses during pregnancy, and to what extent methylation marks evolve during early life, assessing how certain challenges may override some of the effects inherited while in utero. Longitudinal studies are planned to establish associations between early life and first lactation epigenetic marks' memory (methylation and miRNA).

To sum up, different tools can help to address the challenges to produce robust and efficient cattle able to manage the trade-offs between production and adaptation to extreme climate conditions. Figure 3 could be an illustration.

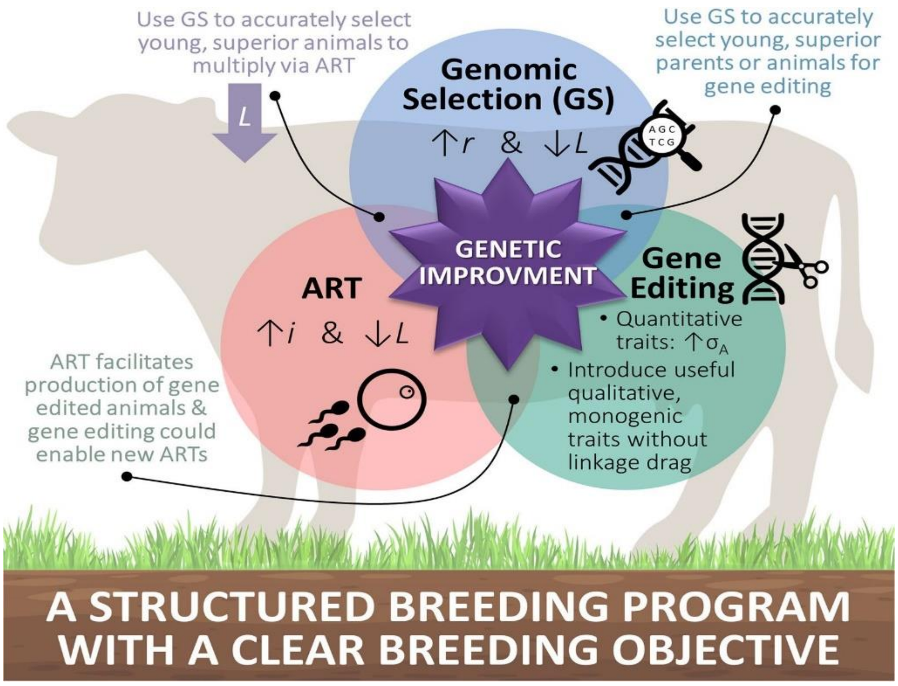

Figure 3. Schematic illustrating the synergistic relationships between genomic selection (GS), assisted reproductive technologies (ART), and gene editing for the genetic improvement of cattle proposed by Mueller and Van Eenennaam (2022). The foundation of genetic improvement is a well-structured breeding program with a clear breeding objective. Within a structured breeding program, reproductive and molecular biotechnologies, such as ART and GS, can be applied to further improve rates of genetic gain by effecting one or more of the components of the breeder's equation (Lush,): (1) increase selection intensity (i), (2) increase selection accuracy (r), (3) decrease the generation interval (L), and (4) increase genetic variation (σ_A)

3.5 Finding the necessary trades-off and balances

The role of the livestock sector in the European and global economy is significant. Food security remains a critical concern in a world where geopolitical tensions are unfortunately on the rise and could worsen if certain regions of the world fail to meet their food needs.

To ensure its sustainability and transition to agroecology, the FAO (2018) recommends harnessing the synergies between livestock and crop production. Integration reduces the need for inputs such as land, water and nutrients and improves overall efficiency. Better integration can be achieved by increasing the proportion of grass, crop residues, by-products and waste that cannot be consumed by humans in livestock feed rations, and by recycling and recovering nutrients and energy from animal waste (e.g. manure management and application, composting and anaerobic digestion for biogas production). Integration can also take place at the landscape or supply chain level. For example, large-scale specialised crop and livestock production systems may link two agroecosystems through trade in feed or manure. However, some dimensions of agroecological transition may be difficult to achieve in these systems, but efforts should be made to minimise waste (Figure 4).

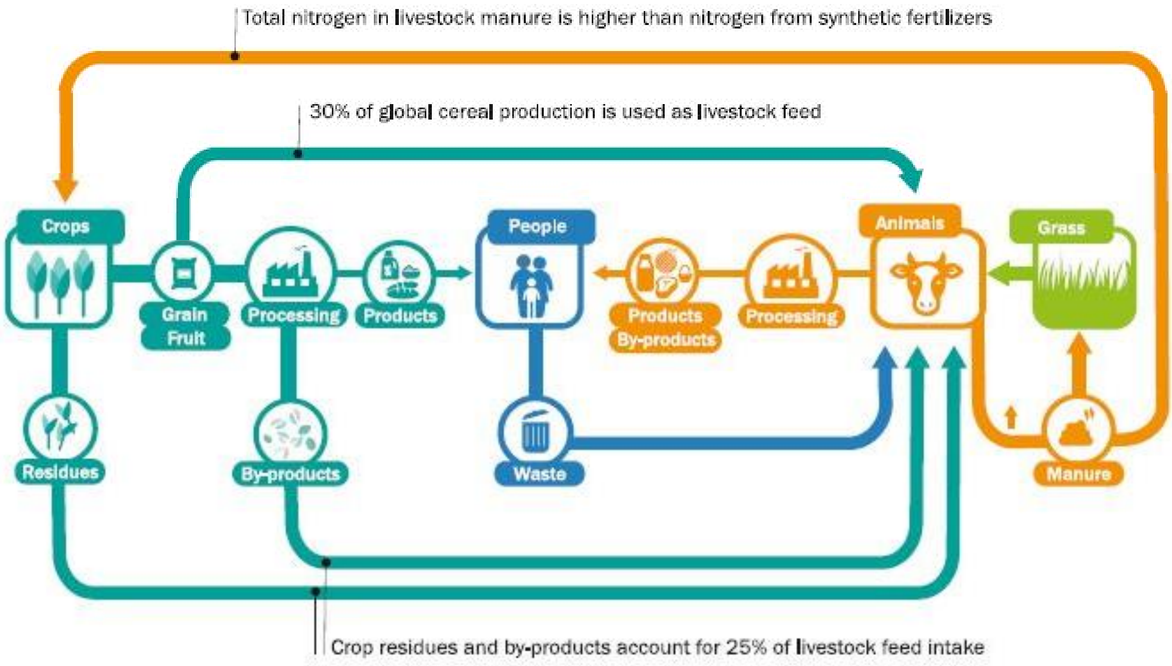

Figure 4. The role of livestock in the bioeconomy [adapted from FAO report - Livestock and agroecology, 2018]

Despite the methodological tools available, it remains difficult to make an overall assessment due to the large number of effects to be considered, their variability between products and production systems and their non-additivity. There are positive aspects associated with products and services, such as landscape maintenance, while other aspects, such as environmental impacts and pressure on resources, generate negative effects. Maintaining the services provided by the former requires, in part, limiting their negative impacts on the latter, which requires trade-offs. This question of trade-offs at the level of livestock systems is often approached in terms of trade-offs between the production of goods on the one hand and environmental impacts on the other, with the aim of reducing environmental impacts without compromising production levels or farmer income.

However, it is the whole system that needs to be balanced. There is no point in reducing direct impacts in one region if this is offset by imports at the expense of another region of the world. It is global sustainability that must be pursued, one that adapts to the evolving society and environment. Sustainability in 2030 will not be the same as sustainability in 2050.

4 Results

In order to construct plausible and contrasting scenarios for the future of livestock farming, the first step was to describe 9 livestock farming systems that can be found in different European regions (Annex 1). These systems were characterised by about forty variables, generally independent of the sector (dairy or meat), defined with ranges of possible variations within the system. Based on these descriptions, 4 contrasting livestock scenarios were developed in which the use of breeding technologies can vary in intensity in order to define the “room of acceptability” for different dimensions by European citizens in the WP2.4.

4.1 Dimensions used to describe the 9 described livestock systems

General aspects of the production system:

- Size (number of productive cows)
- Number of workers
- Use of automation (milking robots, feeding, cleaning, etc.)
- Level of constraint
- Primary feed resources (grass or silage)
- Production level of the herd
- Genetic level of the herd

Health and welfare:

- Impact of system on animal reproduction
- Impact of the system on animal longevity
- Impact of the system on the natural behaviour of the animals
- Impact of the system on animal comfort
- Impact of the system on animal health
- Impact of the system on the need for resistance
- Adaptation of environment to animal needs (ventilation, temperature)
- Control of pathogenic environments
- Consideration of individual nutritional needs
- Impact of system on availability of food resources
- Dependence of the system on external food resources
- Dependence of the system on external material resources

Environmental impact of the system:

- Emphasis on environmental protection
- Multifunctionality
- Greenhouse gases
- Nitrates
- Impact on the forage ecosystem
- Impact on food
- Impact on biodiversity

Production:

- Quantity
- Production quality
- Product standardisation
- Animal longevity
- Animal health

- Animal resilience
- Environmental impact per product unit

Consumer/Market:

- Product price
- Product availability
- Type of valorisation (industrial vs. local)
- Number of intermediaries in supply chain
- Food safety
- Public opinion

Use of Breeding technologies

- Artificial Insemination
- Sexed Semen
- Synchronisation
- MOET
- OPU IVF
- In Vitro Breeding
- Genome Editing
- Genomic Selection
- Epigenomic management

Main genetically selected traits to meet future challenges (depending on livestock systems) : For example : resistance to environmental pathogens, low GHG, Resilience, production level, quality, feed efficiency, health, reproductive ability, robustness/longevity, adapted to climate change…

4.2 4 proposed scenarios

The 4 proposed fictional scenarios on future breeding are the result of collective work carried out at the end of 2022 and during the first half of 2023. They were presented during the annual meeting in June 2023 (Tolède – Spain, June 22 & 23th 2023) and generated numerous reactions and debates. A workshop held during this annual meeting then made it possible to work on each of these scenarios in groups of 10-15 persons and to finalise the proposals contained in this deliverable.

4.2.1 Full throttle towards livestock 2.0

Background: Cattle breeding is the monopoly of a few multinational companies, which have the expertise in all available technologies and propose animal genetics adapted to regional needs. Today's cattle breeds no longer exist as such, apart from selection nuclei maintained as pure breeds, productive animals are crossbred to meet the different challenges they are faced with.

Objectives: High productive animals well adapted to a controlled environment to produce high quantity and standardized quality of products, at affordable prices to feed European citizens and export surpluses to countries that lack them. In order to facilitate rearing and management in a highly controlled and mastered environment, the animals are of a very homogeneous genetic type.

Breeding technologies: In this scenario, a combination of all available technologies (including in vitro reproduction and genome editing, and possibly cloning…) will be used to obtain the desired animals. The next generation will be produced using state-of-the-art breeding technologies such as OPU-IVF MOET with sexed semen and placed on synchronised recipients to reduce the generation interval and maximise genetic progress and spread. High value sexed semen or replacement heifers will be delivered to farms dedicated to milk and/or beef production. Genome editing will maintain/restore genetic diversity in response to specific needs and to meet any future requirements.

Impact on current structures: The number of farms is drastically decreasing (non-renewal of generations and concentration of capital needed for investments: equipment, land...). We can imagine that the farms are very limited in number and very large in size (1000 to 10,000 cows per unit), located close to industrial processing facilities (dairies, slaughterhouses), that make the best use of available resources (animals, feed, labour forces, machinery) are needed to meet consumption needs. Similar to factories, with staff possibly working in 3 shifts with very high-tech equipment, helped with robotic equipment, in controlled environment production units with equipment to limit environmental impact (nitrate and GHG treatments), uniform feeding throughout the year, very homogeneous cows (similar genetics) to facilitate herd management.

There is also a phenomenon of concentration of companies offering genetics. These global companies, of which there are few in Europe, have mastered all the technologies needed to produce animals that meet demand and are constantly adapting to the challenges of tomorrow.

Impact of global warming on cattle: The environment in livestock buildings is highly controlled and adapted to the needs of the animals, both for their primary needs (feeding, hydration, ventilation and atmosphere, light, bedding, exercise) and for their health needs. As the climate warms, controlling the parameters of the sheds environment offers technical solutions to limit heat stress for animals, as well as providing protection from vector-borne diseases such as those transmitted by ticks. Animal welfare is an important consideration on these farms. Depending on the local climate, it may be necessary to change the species of forage to plants less sensitive to droughts, ensuring sufficient supplies for the year.

Environmental impact: Reduced livestock numbers and genetic selection for less GHG-emitting animals with limited non-productive periods can reduce direct GHG emissions and control nitrate emissions through adapted practices. Indirect emissions (feeding practices that require the purchase of non-local feed rather than the use of pasture) remain significant and limit carbon storage. The use of selected plants (possibly genome-edited ones) to maximise carbon storage and resistance to global warming should enable production with fewer inputs (pesticides, fertilisers, etc.) and higher yields per unit area.

Benefits: This breeding system makes it possible to meet the needs of people who, for economic reasons, are forced to base their choice of feed on their budget. The products are available in large quantities and at an affordable price. The more qualitative feeding remain niche markets reserved to the most wealthiest citizens.

The primary needs of the cows are respected in terms of feeding and care, but this system does not allow for individualisation. Animals are selected for high milk production level / average daily gain, resilience and resistance to pathogens in a controlled production environment. Feed efficiency and low methane emission per kg of product are important criteria in breeding objectives.

Risks: In this scenario, where dependence on a few multinational companies is important, the risks can be significant due to high concentration and intellectual property regime. Pathogen resistance, even if selected, does not guarantee against the emergence of new diseases or pathogens. New zoonoses (such as avian flu) could decimate the livestock. Genetic diversity is potentially low, but technological tools such as genome editing allow reversibility. The original breeds have been preserved in cryobanks to allow for any backtracking, adaptation or change of direction that may occur in the future.

Animals are kept in homogeneous batches, where individualisation is not possible due to the size of the farms. Animals that deviate from the standard and show significant variability have no place in this system, which contributes to a sharp reduction in the genetic diversity of cattle populations.

Climate change may lead to major changes in the forage resources available for livestock feed. It may be necessary to adapt cultivated species, in particular by selecting crops that use less water or are more resistant to water stress, in the context of sharing water resources with other users.

The agricultural world has been largely decimated, from the farmer to the companies operating in the sector, and the concentration of activities has led to a significant reduction in the number of companies and jobs. Rural areas are largely affected by this desertification and social issues. As a result of the industrialisation of livestock farming, the social aspects are very pronounced. On the one hand, because of the distance of the population from the farming world is increasing and, on the other hand, because landscape conservation is no longer one of the main functions. Landscapes are changing with these large agricultural structures. The exploitation of large areas is favoured and permanent grasslands are disappearing when the areas have interesting agronomic potential. The poorest areas and mountains are abandoned due to a lack of profitability and turned into forests, with a lack of maintenance and high fire risks for surrounding areas.

To sum up: Livestock production is moving towards an organisation close to that of poultry and pigs (and some areas of the world in cattle as in the USA), pyramidal and highly centralised, in which genetics are controlled by large worldwide breeding companies and widely distributed to breeders. The quasi-monopoly situation and possible patents may entail risks from a market point of view. Cattle are reared on homogeneous and controlled conditions, with the aim of controlling costs and guaranteeing access to protein sources for all citizens in sufficient quantities and at affordable prices. The schemes of supply and demand are redistributed.

4.2.2 Parsimonious breeding

Background: Livestock production is organised around regional/national structures to respond to local needs and issues in terms of territorial organisation. The territorial context and regional products allow know-how and dynamism to be maintained in the different areas. The diversity of European breeds provides important genetic resources that can be used to adapt and become more efficient.

Objectives: Productive animals, pure breeds or crossbreeds, adapted to different production environments in terms of climatic gradients and feed ressources, are present. The quality of the products ranges from the standard, accessible to a large population at affordable prices, to high quality products valued by the processing industry (in particular cheese, matured meat, etc.) with more limited quantities, more remunerative prices for the producer, but access limited to the wealthier population. Some breeds are widespread or at the origin of the main crossbreeds, but regional breeds are still present at a local level, favouring adaptation to the environment and the robustness of the animals in their system. The dairy herd is largely used to support meat production, to the detriment of specialised meat breeds, which are maintained mainly in areas where the land cannot be valorised by crops for human consumption.

Improvements to the objectives are gradual, without disruptions at the level of structures (farms, upstream and downstream sectors) and landscapes. They will take more time but will make it possible to achieve the objectives, particularly in terms of environmental impact (reduction of GHG), optimizing the expression of animal genetic potential through appropriate management…).

Breeding technologies: In this scenario, no technology is prohibited, but its use must address specific needs/issues in terms of adaptation that are difficult to achieve in a limited timeframe with conventional animal breeding. Animal welfare, health, environmental issues (GHG) or stress tolerance are among the issues for which the use of technologies such as genome editing possibly combined with in vitro breeding may be accepted. As genome editing technology is used worldwide and is undetectable as it mimics punctual mutations that may occur spontaneously, European breeding companies, like their competitors outside Europe, must be able to rely on it to produce breeding animals whose widespread use of semen will allow the rapid dissemination of these genetic improvements. Embryo production techniques (OPU-IVF / MOET) are widely used in breeding centres to produce nucleus animals and the use of sexed semen is widespread in order to optimise the production of animals that meet the needs of production and industry.

Impact on current structures: The number of farms is decreasing (non-renewal of generations and concentration of capital needed for investments: equipment, land...). We can imagine that farms will be limited in number and with a moderate to large size (50 to 1000 cows per unit), with a more or less important density depending on the dynamics of the regional area. Robotics systems can be a palliative for labour problems and constraints in the organisation of working time. Feeding the herd with a maximum amount of fodder and protein produced on the farm is a challenge to limit the indirect greenhouse gas emissions associated with importing protein feeds such as soya.

Upstream and downstream businesses are gradually restructuring from the regional level and, for some of them, up to the European level, guided by common orientations. This scenario leaves open the possibility of coexistence between different agricultural systems, including organic farming or quality label systems structured by the valorisation of their products. However, access to land resources can be a difficulty/competition between these different farming systems that do not share a common vision.

Impact of global warming on cattle: The animals are reared in various systems, with sheds that are more or less comfortable for the animals, depending on the size of the herd, local constraints (mountain areas have to cope with both hot and cold periods) and the age of the buildings. In all cases, the most important primary needs are met, even if, depending on the region, there are sometimes feed restrictions in the context of global warming in farms with a pasture-based diet. More recently equipped cow sheds generally provide an environment that is suitable for the welfare of the animals (light, ventilation, etc.). Adaptations to limit the impact of heat waves by controlling the atmosphere/ventilation/misting are usually implemented in regions frequently affected by heat waves to limit the impact on animals and the drop in production. The development of vector-borne diseases, such as those transmitted by ticks or other insects, as a result of global warming, could rapidly become a problem for outdoor animals, leading to the death of the most vulnerable ones. Genetic selection for resistant animals, possibly using breeds from countries that have had to deal with these pathogens, is one possibility.

Depending on the local climate, it may be necessary to change the species of forage to plants less sensitive to droughts, ensuring sufficient supplies for the year. In the context of sharing water resources with other users, the scarcity of these resources must be taken into account in the choice of crop and forage species.

Environmental impact: A significant reduction in the European livestock herd due to cessation of production (retirement, lack of personnel, excessive working hours, low farm income, agribashing, etc.), not fully compensated by an increase in herd size and productivity/genetic progress, etc., will lead to a reduction in GHG emissions. In addition, significant efforts are being made to limit indirect GHG emissions and to make maximum use of grassland and other pastured crops to maximise carbon storage.

Benefits: In this scenario, the agricultural system allows the European population to meet its own consumption needs without the objective of developing an export market. Products are available in sufficient quantities and at competitive prices to ensure access for most of citizen, although some higher quality products are available in smaller quantities / more expensive prices and therefore reserved for wealthier citizens. Animal welfare, health and feeding are of paramount importance and high standards are maintained. After half a century of selection for productivity and product quality, animals are now selected to meet agro-ecological challenges and sustainability needs: health, disease and pathogen resistance, environmental resilience and limited environmental impact (GHG) are the main objectives. Herd renewal needs are controlled and planned, allowing greater efficiency in production and working time for breeders.

In this scenario, the social aspects and links between livestock farmers and rural dwellers are fairly well preserved in areas where livestock farming remains important. The presence of livestock continues to structure the landscape, with changes depending on local circumstances.

Risks: In this scenario, risks are measured. The 'moderate' size of production units and the high proportion of the animals fed indoors should make it possible to control both the risks of heat stress and the emergence of new zoonoses that cows could suffer as a result of global warming.

Good management of genetic diversity, inbreeding and genetic load, and the possible introduction of genetic resources adapted to climate change through crossbreeding or genome editing techniques will limit major loss of genetic variability. All genetic 'improvements' through selection or technology (genome editing) must be reversible if they prove to be detrimental over time.

Climate change will also mean that the forage crops used to feed livestock will need to be adapted, with varieties or forage species that are more resilient to water shortages, or that can be grown earlier to produce forage at the most favourable periods.

To sum up: Livestock breeding is adapting to the needs of climate change adaptation in terms of production system/animal adaptation, but also in terms of limiting the carbon footprint of livestock production by using the different levers at its disposal, including genome editing, to adapt rapidly while ensuring wide access of the European population to protein sources in sufficient quantities and at affordable prices.

4.2.3 Status quo

Background: Breeders and breeding companies are unable/lack a clear vision to define and implement strategies adapted to the challenges of reducing the carbon footprint in order to maintain livestock production as an important source of protein financially accessible to European citizens. lack of ambitious policies and technical means to achieve the objectives leaves room for demobilisation and a wait-and-see attitude in a generally unfavourable context (age pyramid with many retirements not replaced, importance of financial needs to take over a farm, lack of price prospects, agri-bashing) and in competition with other uses of agricultural land (cereals, industrial crops, biomass production for biogas / energy production)).

Objectives: European livestock farming is in slow decline, often without any real objective other than to manage an inexorable decline according to a national/regional context. Several breeds coexist, sometimes crossbred, in order to meet the needs of historical sectors, which are not necessarily in line with current needs (adaptation to a changing production environment, in particular due to climate change). To limit the environmental impact of ruminants and feeding costs, farmers have been encouraged to maximise grazing. Maintaining (slowing down the decline of) the sector linked to livestock production and its upstream and downstream chains is a challenge in a context of competition at territorial level between livestock production and other activities that are more remunerative (energy production) or require less labour (crops).

Breeding technologies: In this scenario, the use of new technologies, such as genome editing or in vitro breeding, is subject to European consultation and approval, which significantly lengthen the process and contribute to penalising stakeholders who do not have the same tools as their worldwide competing companies. The debate on such technologies concerns all species, but is even more acute in the case of animal species. However, the question arises as to how to manage the use of semen produced outside Europe, in countries where animal genome edition is permitted, when it cannot be detected ? This competitive disadvantage may lead to a lack of investment in mastering these technologies and possible dependency and/or contribute to a general demobilisation of the industry.

The methods currently used in the 2020s have not be called into question, whether in terms of shortening the generation interval or multiplying high-potential individuals through embryo production (OPU-IVF / MOET), selecting the sex of animals of interest through the use of sexed semen, or selection tools such as genotyping and genomic selection. But whatever the technology used, the main question remains its economic interest, which in most cases is very limited.

Impact on current structures: An unfavourable age pyramid, the increase in the average size of farms (and therefore an investment considered impossible for non-family investors) and the current agri-bashing does not contribute to a positive dynamic in the sector. If we take into account the fact that the European population is limiting or even reducing its consumption of beef due to inflation and environmental considerations, or is shifting towards the consumption of species such as poultry or pork, which are more feed efficient and have a smaller carbon footprint, the decline seems to be in line with this trend.

This situation is leading to a reduction in the number of farms. The remaining farms have stable herd sizes overall and are discouraged by the investment required for expansion and the lack of long-term prospects. Depending on opportunities and the market, some farms may increase their herd size. The smallest farms are gradually disappearing and the average herd size is between 100 and 200 head.

The whole livestock sector is depressed by the lack of prospects, which also affects upstream and downstream sectors. Depending on its agronomic potential, the land freed up by livestock farming is replaced by crops or converted into forest. Landscapes are gradually changing and the network of mutual support in the farming world is becoming more distant as the number of farmers decreases.

Impact of global warming on cattle: In this scenario, maximising grazing remains an objective. However, depending on the geographical area, in the context of global warming, rainfall between May and September may be limited and production drastically reduced. Supplementing with stocks is essential. On the other hand, the beginning and the end of the grazing season can be quite favourable. The absence of a real cold season in certain geographical areas and greater difficulties of controlling the presence of pathogens in an open environment such as grazing area contribute to an increase in vector-borne diseases (Bluetongue, Schmallenberg, besnoitiosis, ehrlichiosis, etc.) and multiply their impact. It could rapidly become a problem for outdoor animals, leading to the death of the most vulnerable ones. Genetic selection for resistant animals, possibly using breeds from countries that have had to deal with these pathogens, is one possibility.

For animals that remain indoor, the sheds are more or less comfortable, depending on local constraints (mountain areas have to cope with both hot and cold periods) and the age of the buildings. In the context of global warming, the animal welfare is highly variable and largely depends on the farm, the geographical area and its climate, the physical layout of the shed (air circulation, ventilation, misting, etc.). In indoor conditions, the development of vector-borne diseases can be considered under controlled. In this wait-and-see context, investment to limit the impact of heatwaves on animals remains limited.

Depending on the local climate, it may be necessary to change the species of forage to plants less sensitive to droughts, ensuring sufficient supplies for the year.

Environmental impact: The reduction in the direct environmental impact is made possible by a significant reduction in livestock stocks in most European countries, but not by improving efficiency or redesigning livestock production systems. From a European perspective, it may appear that the climate impact of ruminant livestock production is decreasing if we considered only direct impact. Although some beef has been switched to other animal proteins (chicken/pork) with lower GHG emissions, the European population, which is well off in global terms, continues to consume beef proteins, some of which are imported to compensate for the decline in European production. In such a situation, to the GHG emissions associated with livestock production, we must add the GHGs associated with product transport.

Benefits: European product quality standards remain high (animal welfare, livestock feeding, etc.). Breeders continue to select animals for their robustness (resistance to disease, resilience, etc.) in order to facilitate their work and limit costs. The amount of product available is limited, which increases selling prices and could lead to an improvement in farmers' incomes.

Risks: The risks with this scenario are significant at various levels of society. In the medium term, food sovereignty is not guaranteed for beef meat and dairy products. The increase in the price of locally/regionally produced products, which accelerates the decline in consumption.

For consumers, the lack of European production leads to higher prices and some European consumers turn to cheaper imported products produced to much lower standards, and with a higher indirect environmental impact than if it had been produced in European countries.

For breeders, the lack of career prospects prevents young people from planning ahead and taking over farms, especially as the work can be physically demanding, poorly paid and requires a lot of sacrifice (no weekends, few holidays, etc., which the younger generations are less willing to accept than in the past). Only a few high value-added sectors (cheese, etc.) are dynamic in terms of installation of young farmers.

For upstream and downstream of dairy and meat sectors, this slow decline leads to a significant reduction in employment in agro-industrial companies.

In the genetics sector in particular, the gap is widening between European companies/breeders, whose regulatory constraints may limit the use of techniques such as genome editing, and countries that can use these approaches as a result of a competitive advantage in genetic progress. As the size of European breed populations is expected to decline, genetic progress will be reduced due to a lower intensity of selection. Genetic diversity may also be reduced by the reduction in population size, although the use of cryobanks can help to preserve it.

Climate change will also mean that the forage crops used to feed livestock will need to be adapted, with varieties or forage species that are more resilient to water shortages, or that can be grown earlier to produce forage at the most favourable periods.

To sum up: The decline of livestock farming is being accelerated by the lack of clear prospects for the future. Young people are reluctant to enter this profession. Wealthy European citizens can continue to consume European products, while the less well-off may be forced to turn to imported products from countries that do not have the same production standards and emit more GHG.

4.2.4 Livestock: a social contract

Background: Society as a whole is rejecting animal production, particularly that of ruminants, as too polluting in relation to services it provides. Consumption of animal proteins, particularly from cattle, is declining rapidly, a phenomenon accelerated by the ever-increasing prices, combined with the scarcity of products produced in Europe, which are becoming veritable niche products reserved for the wealthy. Low and middle class populations have been deprived of cattle protein sources or forced to buy imported products that do not meet existing European standards.

Objectives: The remaining animal populations respond to a social contract for the conservation of natural areas. Livestock help to maintain the landscape in areas where crops and mechanisation are not possible (mountain pastures, the limestone plateaus, etc.). Agroforestry also meets expectations and the benefits are multiple (animal welfare in times of heat stress, additional fodder in times of drought) and reciprocal (soil fertility through animal manure). The products of these sectors are well paid because of their scarcity and the high added value developed by these sectors (in particular through cheese, etc.) or because they respond to very specific needs (nutritional needs with infant milk powder, etc.). The cattle that meet these needs are pure-bred or crossbred from local breeds selected for their adaptation to this harsh environment (use of roughage, hardiness).

Breeding technologies: In this scenario, new technologies that accelerate genetic progress, such as genome editing or in vitro breeding, have no place for a number of reasons. Legally, society's rejection of animal production is also a rejection of anything that could be likened to genetic manipulation, even if it is equivalent to spontaneous mutation. But the main reason is that these cutting-edge technologies are costly (especially as they are not used on a large scale) and the economic context of cattle farming in Europe does not allow such investments to be profitable from an economic point of view. Even certain techniques traditionally used in selection nuclei, such as embryo production (OPU-IVF/MOET), are struggling to find their place for economic reasons. Genetic selection based on genotyping techniques and used of sexed semen is considered to be largely sufficient to meet reduced needs, especially in the absence of competitive issues. Genetic diversity is conserved at the European level, as the remaining animals generally come from small, locally adapted and robust populations. The reduction in population size may reduce genetic diversity within the breed, but the use of cryobanks may help to preserve this variability.

Impact on current structures: The current structures have largely disappeared over time, with an age pyramid that favours strong regression. The remaining cattle farms are small (40 to 100 cows) and located in well-defined geographical areas, where the land is not suitable for cultivation (soil type, slope, etc.). Landscapes are gradually changing. Depending on its agronomic potential, the land freed up by livestock farming is replaced by monogastric (pork or poultry), which is more efficient in terms of feed conversion and emits fewer GHG, crops adapted to global warming (possibly to produce the biomass needed for biogaz) or forests have developed in the uncultivated areas.

The network of mutual support in the farming world is becoming more distant as the number of farmers decreases. Upstream and downstream sectors have been largely affected by these reorientations.

Impact of global warming on cattle: In this scenario, the aim is for livestock to make best use of areas that would otherwise remain uncultivated, and therefore to graze these areas. Feeding these animals is highly dependent on available feed resources, which are weather dependent and therefore more variable because of global warming.

Stable facilities are relatively basic in a context of limited investment, which can be detrimental to the animals, particularly in the event of a heatwave. Agroforestry can be a winning combination, providing shade for animals and food resources in times of drought.

The absence of a real cold season in certain geographical areas and greater difficulties of controlling the presence of pathogens in an open environment such as grazing area contribute to an increase in vector-borne diseases (Bluetongue, Schmallenberg, besnoitiosis, ehrlichiosis, etc.) and multiply their impact. It could rapidly become a problem in some areas leading to the death of the most vulnerable animals. Genetic selection for resistant animals, possibly using regional breeds or breeds from countries that have had to deal with these pathogens, is one possibility.

In this scenario, cattle are highly dependent on global warming and have little leverage.

Environmental impact: The direct environmental impact at European level is largely reduced, with significant reductions in greenhouse gas emissions and nitrate production due to the significant reduction in livestock numbers. The indirect impact is much less favourable, as part of the population continues to consume cattle protein (milk and meat), but it has travelled across the planet... but here we turn a blind eye.

Livestock farmers have a social contract with society to maintain the landscape. By grazing in areas that are difficult to access and often have very low agronomic potential, cattle help to enhance the value of these areas, promote biodiversity in flora and fauna, and help to store carbon in the soil, thereby reducing greenhouse gas emissions. Their grazing also reduces the risk of fire and limits the use of pesticides.

Benefits: In this scenario, the European agricultural system will no longer be able to feed its citizens its citizens who wish to continue eating red meat and dairy products but it is adopted in the context of environmental beliefs. In addition to the environmental benefits associated with reduced greenhouse gas emissions due to the significant reduction in cattle numbers, reduced meat consumption is perceived as a health benefit. Some of the consumption of animal protein has been redirected towards poultry and pork, which is more feed efficient and less GHG emitting.

Cattle herd management is much more extensive, taking advantage of the natural resources available nearby. Cattle are reared in a natural environment with fewer external resources. These animals have been selected for their robustness and resilience in their environment. Regional breeds or crossbred animals are preferred as they are better adapted to the environment and more robust.

With low operating costs due to the use of land with low agronomic potential and much higher product prices due to the limited quantity of products (meat and/or milk), farmers are able to earn a return on their labour.

Risks: The risks with this scenario are significant at various levels of society. Cattle food sovereignty is not guaranteed at short-medium term.

For consumers, the consumption of protein from cattle is still much higher than European production, leading to a large trade deficit. The lack of European production leads to higher prices and some European consumers turn to cheaper imported products with production standards often lower than European standards (possible use of antibiotics, growth hormones…), less frequent and less rigorous controls..., and finally with a higher environmental impact, if indirect emissions related to transport are included, than if it had been produced in European countries.

The dairy and meat sectors are also experiencing this change, leading to a large reduction in employment in agro-industrial companies and a significant increase in consumption of processed products from outside Europe.

And as for the genetic sector, it has almost completely disappeared because the need and the market is too limited. Genetic selection tools are limited because reference populations are very limited. Genetic diversity is greatly reduced by the decline in population size and even the disappearance of some European breeds. The use of cryobanks can help to preserve genetic material for possible future use.

For livestock, access to veterinary and other services is becoming increasingly difficult due to a shortage of practitioners. There are fewer and fewer rural vets due to lack of demand and long distances.

In this scenario, the risks associated with the development of monocultures or limited crop rotation on land previously used for cattle farming are numerous:

- an increase in the incidence of diseases and pests and hence the need for phytosanitary treatments,
- an increase in dependence on synthetic fertilisers
- the impoverishment of soils as a result of a decline in organic matter levels, leading to a loss of fertility and greater vulnerability to erosion.

To sum up: The decline of livestock is a societal response to environmental needs without taking into account the indirect environmental impacts and the risks of dependency on third countries. The role of cattle is mainly limited to landscape maintenance in some areas. Related production is reserved for niche markets.

5 Conclusion

Similar to the vast majority of developed countries, European societies are witnessing a weakening of the link between people and nature. Citizen-consumers, now predominantly urban or peri-urban, have lost their links with rural life and are unfamiliar with the realities and practices of agriculture. In this context, a movement of distrust towards livestock activities is growing, driven by various concerns (animal welfare, environmental impact of livestock farming, etc.) and an increasingly anthropocentric view of animals. The evolution of livestock farming must take into account both the changing expectations of society and the imperative need to adapt to climate change and the commitment to mitigate global warming, in particular by developing practices that promote carbon sequestration in soils and reduce greenhouse gas emissions. However, this development must also take account of the concerns of farmers, who are faced with numerous challenges (significant reduction in their numbers due to retirement and lack of replacements; difficulties in recruiting labour and taking holidays; increasingly large investments; growing administrative constraints, etc.). The lack of recognition of their profession and the lack of prospects lead to discouragement.

The disappearance of livestock is not the answer. From a nutritional point of view, animal proteins comply with global dietary recommendations, even if the demand for bovine protein is decreasing in Europe, this is not the case on a global scale. The solution of importing beef and dairy products and thus relocating production is unsatisfactory for a number of reasons, including issues of food sovereignty and security (guarantees in terms of quantity, price, quality, especially food safety). Moreover, the absence of a mirror clause means that imported products are generally of lower quality than European standards. On the other hand, cattle farming provides a large number of ecosystem services that should not be overlooked, in particular through the valorisation of grasslands. In certain areas, it maintains the landscape, and its disappearance would lead to profound changes: expansion of wooded areas, loss of population and reduced attractiveness of areas. It is necessary to redesign ruminant livestock systems that are:

1) better adapted to environmental, climatic and biodiversity challenges, with a reduced carbon footprint, ensuring feed autonomy to meet dietary needs in terms of energy and protein through multi-species fodder and pasture production, including legumes, sufficiently diversified, and allowing for creation of reserves for periods that are too dry or too wet;
2) with more robust animals (through selected breeds or crossbred animals) adapted to the available fodder resources and whose production system is in line with the seasonality of these fodder resources, resistant to numerous pathogens and of a adapted size to maximise access to pastures;
3) in line with societal expectations, particularly in terms of well-being, to which the One Health and One Welfare initiatives contribute.

The complexity and interconnectedness of the issues show that compromises are necessary and that there is no one-size-fits-all system. It is essential to tailor responses to each system, or even each farm, in order to find the best possible balance in terms of sustainability, taking into account the specific area. However, it is crucial to remember that the equation needs to be optimised not only locally, but also nationally and even globally to minimise the impact on our planet. The perfect system does not exist.

sector that contributes to sustainability at the global level

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7 Annex

	Dimension	Sub-dimension	Scores Interpretation: low score	Scores Interpretation: high score	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9
					Factory farms	*Automatised farms*	*Intensive - hypertype farms*	*Traditionnal - Family Farms*	*Low input / seasonal farms*	*Low working time (once milking/day)*	*processed - quality signs /*	*Organic farms*	*landscape keeper - double active*
Farm system & animal	Farm size (#cows)				400-2000	50-400	100-400	50-150	50-150	50-150	40-100	40-100	1-20
	#worker				large number	1-3	2-5	1-2	1-2	1	1-2	1-5	1 (partial time)
	Main forage				Silage	Silage	Silage	Mix Past. / silage	Past. / hay-silage	Past. / hay-silage	Pasture / hay	Past. / hay-silage	Pasture
	Robotic uses (milking, feeding, cleaning...)		low use of robotics	high use of robotics	3-7	8-10	3-7	0-3	0-2	0-2	0-3	0-3	0
	on-call level for breeders (niveau d'astreinte)		strong on-call	no on-call	5-7 (employees)	7-10	0-3	0-5	3-7	5-10	3-7	3-7	10
	Animal production level		low production level	High production level	6-8	7-10	9-10	3-8	2-6	2-4	2-6	2-6	0
	Genetic level		No specific use of genetic information	Large use of genetics information	2-7	5-10	7-10	2-7	0-7	0-5	0-7	0-5	0
	Reproduction		High demand. (period constraints, trade-off)	Low demanding reproduction system	3-5	3-5	0-3	3-8	0-2	5-10	5-10	5-10	8-10
	Longevity - productive life (impact of system on animal longevity)		Large impact	No impact	0-5	3-7	3-7	5-10	0-5	5-10	7-10	5-10	5-10
	Animal Welfare (impact of system on animal ...)	natural behaviour	Large impact	No impact	0-3	3-5	0-3	3-7	3-7	3-7	3-7	3-7	10
		Comfort	no consideration	great consideration	0-5	5-10	5-10	3-7	0-5	0-5	3-7	3-7	0-5
	Environmental control	ventilation, temperature	No control	full control	5-10	5-10	5-10	0-7	0-3	0-3	0-7	0-7	0
		Pathogens	No control	full control	5-10	5-10	5-10	3-10	0-5	0-5	3-10	0-5	0
	Animal Feeding		No management (ressources dependencies)	management in relation to needs	5-7	8-10	8-10	8-10	0-5	0-5	5-7	0-7	0
	Environmental resilience (dry period, flooding...)		high dependency	No dependency	8-10	8-10	8-10	0-10	0-3	0-5	0-5	0-5	0
	System resilience (feed supplier, Electronic supplier...)		high dependency	No dependency	0-3	0-3	3-7	3-7	8-10	8-10	5-7	5-7	10
Environment	Landscape keeper		No consideration to landscape	large consideration to landscape	0	0-3	0-5	5-10	7-10	7-10	5-10	5-10	10
	multifonctionality (nourricier / entretien)		No multifonctionality	High level of multifonctionality	0	0	0-3	3-10	5-10	3-10	5-10	5-10	7-10
	Environmental impact	GHG / NO3	Large GHG/NO3 emission / unit product	Low GHG / NO3 emission / unit product	5-7	5-10	7-10	5-7	3-5	3-5	3-5	3-5	0-3
		Pasture - Forage ecosystems	Bad impact on pasture/forage ecosyst.	Good impact on pasture/forage ecosyst.	0	0-3	0-3	3-10	5-10	5-10	5-10	7-10	7-10
		Animal Feeding	Large environm. impact of animal feeding	Low environm. impact of animal feeding	0-3	0-5	0-5	3-7	7-10	5-10	5-10	7-10	10
	Impact on biodiversity		Loss of biodiversity / genetic ressource	Enhancing biodiversity / genetic ressource	0-3	0-5	0-3	3-10	3-10	3-10	5-10	3-10	0-10
Consistency with overall objectives	Quantity of products		Low quantity of products	Large quantity of products	7-10	7-10	10	5-7	2-6	2-4	2-5	2-5	0
	Quality of products		Low quality of products	High quality of products	2-5	2-5	2-5	3-7	3-7	3-7	7-10	7-10	2-5
	Standardisation of products		Heterogeneous products	Homogeneous products	10	10	10	3-7	2-5	2-5	2-5	2-5	0
	Longevity of animals / Animal Health		Low longevity / poor health of animals	High longevity / good health of animals	1-5	3-7	3-7	5-10	0-5	5-10	7-10	5-10	5-10
	Resilience of animals		low resilience	High resilience	0-3	0-3	0-3	3-7	5-10	3-7	5-10	3-7	5-10
	Environmental impact (GHG...) per farm		High environmental impact per farm	Low environmental impact per ferm	0-2	3-5	3-5	4-6	6-8	6-8	8-10	8-10	10
	Environmental impact (GHG...) per unit of product (/kg of protein)		High environmental impact	Low environmental impact	5-7	5-7	7-10	5-8	3-7	3-5	3-7	3-7	0-3
Consummer	Affordability	price for customer	High price	Low price	10	8	8	6	6	6	4	2	-
		local economy - #intermediaries	national / international - #intermediairies	local economy - direct selling	0	0	0	0-5	3-7	3-5	5-10	5-10	10
	Public opinion		Poor opinion	Good opinion	0	2-5	0-5	3-7	7-10	3-7	7-8	8-10	5-10
	food safety		Food insecure	High level of food safety	3-7	5-10	5-10	5-10	3-7	3-7	7-10	5-10	-
	Food self-sufficiency		No self-sufficiency	large self sufficiency	10	10	10	7-10	3-5	3-5	3-7	3-7	0
Selection Approach	Artificial Insemination		no use of IA	large use of IA	10	10	10	5-10	0-7	0-3	0-5	0-5	0
	Sexed Semen / Sexed Embryo		no use of sexed semen / Embryo techn.	large use of sexed semen / Embryo techn.	10	10	10	5-10	0-5	0-3	0-5	0-5	0
	MOET (Multiple Ovulation Embryo Transfert)		no use of MOET technologies	large use of MOET tech	0-3	3-7	7-10	3-7	0	0	0	0	0
	OPU IVF (Oocyte pick-up - In vitro fertilisation)		no use of OPU-IVF technologies	large use of OPU-IVF technologies	0	3-7	7-10	3-7	0	0	0	0	0
	Genome Editing		no use of genome editing techn.	large use of genome editing techn.	10	10	10	3-7	0	0	0-3	0-3	0
	Genomic Selection		no use of genomic selection techn.	large use of genomic selection techn.	0-7	3-10	10	3-10	0-5	0-3	0-7	0-7	0
	Epigenetic		no use of epigenetic information techn.	large use of epigenetic information techn.	0-5	3-7	7-10	3-7	0	0	0-5	0-5	0

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