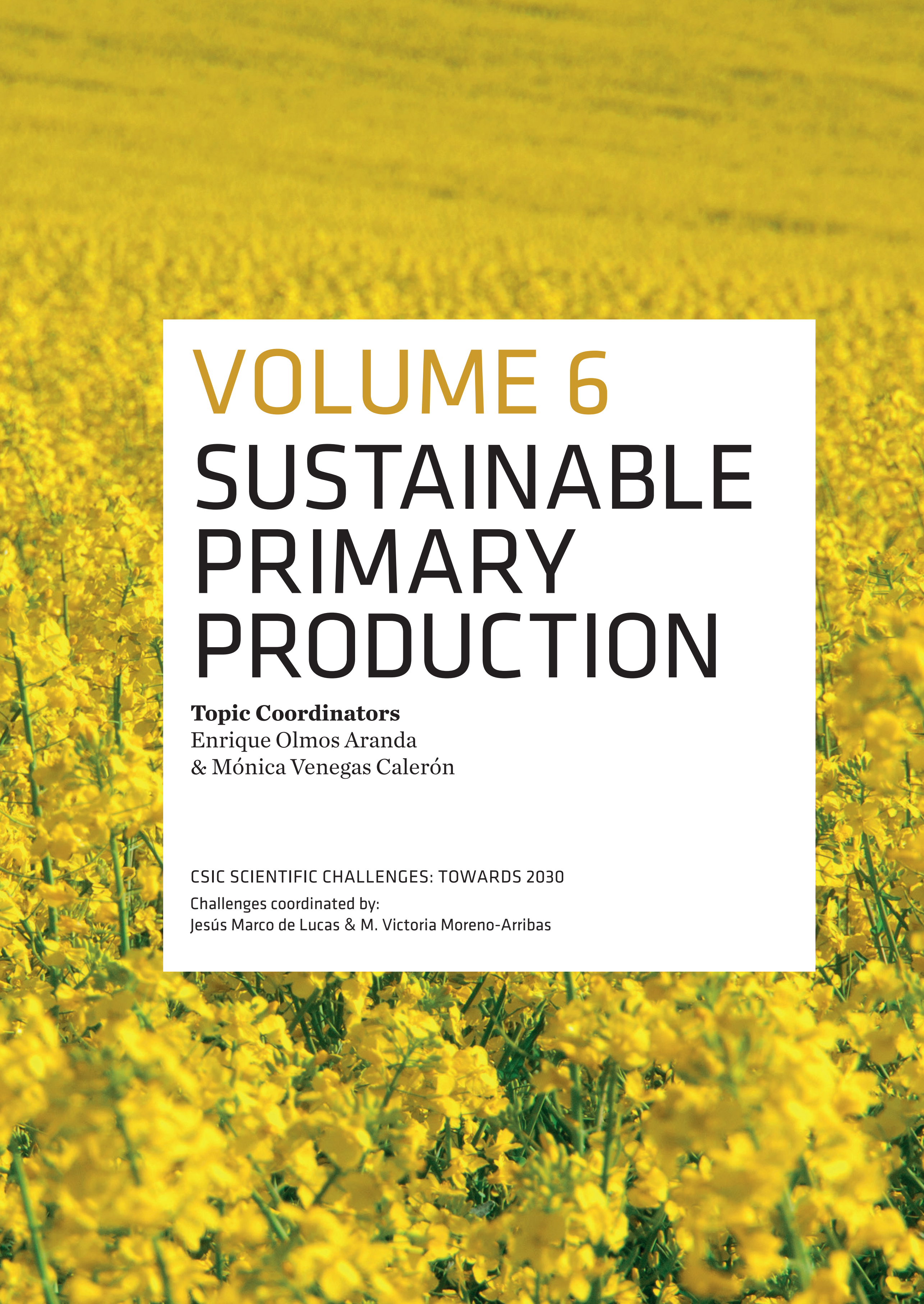

VOLUME 6
SUSTAINABLE PRIMARY PRODUCTION

Topic Coordinators
Enrique Olmos Aranda
& Mónica Venegas Calerón

CSIC SCIENTIFIC CHALLENGES: TOWARDS 2030

Challenges coordinated by:
Jesús Marco de Lucas & M. Victoria Moreno-Arribas

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SUSTAINABLE PRIMARY PRODUCTION

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CSIC SCIENTIFIC CHALLENGES: TOWARDS 2030

What are the major scientific challenges of the first half of the 21st century? Can we establish the priorities for the future? How should the scientific community tackle them?

This book presents the reflections of the Spanish National Research Council (CSIC) on 14 strategic themes established on the basis of their scientific impact and social importance.

Fundamental questions are addressed, including the origin of life, the exploration of the universe, artificial intelligence, the development of clean, safe and efficient energy or the understanding of brain function. The document identifies complex challenges in areas such as health and social sciences and the selected strategic themes cover both basic issues and potential applications of knowledge. Nearly 1,100 researchers from more than 100 CSIC centres and other institutions (public research organisations, universities, etc.) have participated in this analysis. All agree on the need for a multidisciplinary approach and the promotion of collaborative research to enable the implementation of ambitious projects focused on specific topics.

These 14 "White Papers", designed to serve as a frame of reference for the development of the institution's scientific strategy, will provide an insight into the research currently being accomplished at the CSIC, and at the same time, build a global vision of what will be the key scientific challenges over the next decade.

VOLUMES THAT MAKE UP THE WORK

1 *New Foundations for a Sustainable Global Society*
2 *Origins, (Co)Evolution, Diversity and Synthesis of Life*
3 *Genome & Epigenetics*
4 *Challenges in Biomedicine and Health*
5 *Brain, Mind & Behaviour*
6 *Sustainable Primary Production*
7 *Global Change Impacts*
8 *Clean, Safe and Efficient Energy*
9 *Understanding the Basic Components of the Universe, its Structure and Evolution*
10 *Digital and Complex Information*
11 *Artificial Intelligence, Robotics and Data Science*
12 *Our Future? Space, Colonization and Exploration*
13 *Ocean Science Challenges for 2030*
14 *Dynamic Earth: Probing the Past, Preparing for the Future*

CSIC scientific challenges: towards 2030
Challenges coordinated by:
Jesus Marco de Lucas & M. Victoria Moreno-Arribas

Volume 6
Sustainable Primary Production

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CONTENIDO

ABSTRACT

This volume illustrates the main research issues for the development of an environmental and economical sustainable primary production. An interdisciplinary collaboration between several scientific areas has allowed the study of the future evolution of agriculture, livestock and food production. The first chapters analyze the proper balance between productivity and environmental goals in agriculture and how to reduce its impact on ecosystems. Subsequently, the following chapters discuss the improvement of livestock and aquatic systems. Besides, new approaches in plant health, plant biotechnology and plant breeding are also described according to a future sustainable production. To conclude, the final chapters suggest the novel and future approaches in food production and food safety.

KEYWORDS

ecosystem services | biodiversity | agroecology | circular bioeconomy | animal health and welfare | aquaculture | plant health | pests | genome-editing | synthetic biology | functional food | food industry 4.0 | emerging risks | food safety

EXECUTIVE SUMMARY

The current model of development and consumption generates a high environmental impact, in some instances difficult to reverse. Sustainable primary production is a respectful manner to adapt to the new conditions and act as mitigators of Climate Change and protect biodiversity. It is essential to find solutions by seeking harmony, restoring human-nature relationships, through optimal, respectful and sustainable management of agro-ecosystems and livestock production promoting basic and applied research.

In this book we summarize the most relevant challenges that must tackle in the coming years to achieve a more efficient and respectful use of natural resources, including land and marine agricultural inputs. These challenges are covered into 7 chapters:

1. Agriculture ecosystem services
2. Agroecology and circular bioeconomy
3. Comprehensive improvement of livestock and aquatic systems
4. Plant health. Resistance to pests and diseases
5. Biotechnology and plant breeding
6. Sustainable production in the food industry
7. Food safety

PREFACE

It is difficult to imagine a world today without agriculture and livestock. However, until the last glaciation (≈11,000 years ago), human social groups were made up of hunter-gatherers who lived from hunting, fruit gathering and fishing and were distinguished by their capacity for mobility. About 10,000 years ago, a turning point in human history took place. Progressively, these groups became sedentary with the creation of the first settlements, coinciding with the development of the first domesticated species of plants and animals that allowed them to be producers of their own food. In the following millennia, the progressive development of agriculture, livestock and fishing took place in different parts of the world allowing the increase of the world population in parallel. From the end of the 19th century and the beginning of the 20th century, industrialization and the development of chemical fertilizers and pesticides gave an important impulse to the increase of agricultural and livestock production in the world, allowing the population to multiply by seven in the last 200 years. Never in the history of mankind have had access to such amount of high quality food. However, we cannot ignore the high environmental costs of development, known in numerous impacts, from the decrease of biodiversity in large areas, the eutrophication of aquatic ecosystems due to the excessive input of nutrients in hydrological and sedimentary flows, to the proliferation of the use of food packaging systems, as well as production and distribution chains, with a high environmental footprint.

The Earth's resources are adequate to meet the current demand for food. However, as the human population continues to increase, and historical consumption patterns change and expand, as a result of increasing economic wealth, the need for more demand-driven, waste-free production is inexorable. Under current pressures, according to the United Nations, the world's population will be approximately 9,7 billion by 2050, and according to FAO, an increase of more than 70% in current food production will be required to feed this population. Therefore, in the next 50 years we must produce as much food as it has been produced in history (Megan Clark, former director of the CSIRO).

Considering that the planet's resources are finite and there are limits based on the planet's capacity to renew them, and to absorb impacts without catastrophic changes, research is needed to develop strategies for sustainable development in agriculture. The concept of "sustainable development" was presented by the World Commission on Environment and Development (WCED) in 1987 —known as the Brundtland Report— as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. Sustainable development is based on the acceptance that development is both possible and necessary; that it must be made sustainable, enduring and achievable over time; and that it must fulfilled a threefold function: economic growth, social equity and environmental problems.

The current model of development and consumption —including the current agricultural systems— generates, in its great majority, a high environmental impact through different processes of land degradation, which have led in several occasions to changes in biodiversity of difficult reversibility. This situation is complicated both by regional aspects (in terms of primary production, processing and supply chain to the end user) and by greater global fluctuation in the demands of a specific food. In addition, in a global context, enormous challenges appear associated with a changing climate scenario, which forces us to continue producing, consuming fewer resources, adapting practices and technology to new environmental conditions and generating mitigation scenarios in the face of the climate emergency. In addition to producing quality food in a respectful manner in the face of growing demand, agricultural systems are challenged to adapt to the new conditions and have the opportunity to act as mitigators of Climate Change and protect biodiversity. The protection of biodiversity, with its buffer and dilution effect, is also a key factor in the face of another global challenge, namely the prevention of pandemics, with the unprepared and global scourge of the current COVID-19, which we must incorporate into our current range of threats. Finally, there is the continuing dilemma of having a finite amount of land available for agriculture and livestock.

Awareness of the global nature and the impact of our actions force us to proceed to avoid the irreversible effects. All of these factors point to the need for more efficient production of crops with optimized traits intended as a whole for primary products and co-products. It is essential to find solutions by seeking harmony, restoring human-nature relationships, through optimal, respectful and sustainable management of agro-ecosystems and promoting basic and applied research. With this approach, innovative responses, the implementation of decentralized systems adapted to local situations, the use of appropriate technologies, new production processes can achieve a more efficient and respectful use of natural resources, including land and marine agricultural inputs. We summarize below the research challenges proposed for the achievement of sustainable primary production.

(i) Sustainable agricultural and food systems, which combine preservation of the natural environment with food production, in addition to producing food for society, generate many ecosystem services that are essential to its well-being. Our society today faces the challenge of valuing these ecosystem services from natural and agricultural systems that will enable us to improve the health, economy and quality of life of people today and in future generations. It is not sustainable to deplete resources and degrade ecosystems in order to produce food, agriculture and biodiversity cannot be opposed but complementary, co-working for food production and the generation of ecosystem services. Even so, the conversion of natural areas, or traditional agricultural systems, into areas of intensive agricultural monoculture is advancing unstoppably, causing various processes of ecosystem degradation and loss of biodiversity, directly affecting climate change and deteriorating numerous ecosystem services. Thus, a key objective now is the imminent evolution towards a sustainable intensification of agricultural and livestock systems, where sustainable agricultural and livestock practices and management are compatible with the production of sufficient and quality food, without impairing fundamental ecosystem services for other socio-economic sectors (e.g. tourism, provision of common household goods) and for social welfare (e.g. flood regulation, erosion and pollution control, human health, quality of life, recreation). Various studies show that it is possible to combine sustainable agricultural practices that preserve the optimal quality and functions of soils and vegetation on a small scale, without negatively affecting or even increasing productivity. Experiences with agro-ecosystem management need to be tested, validated and extrapolated to a larger scale in order to develop sustainable extensive and intensive agriculture. All this can only be done by knowing the impacts of agriculture on the socio-ecological systems, from the most updated research hand in hand with social acceptance and consensus of the actors involved, with agro-ecological keys.

(ii) The multidisciplinary approach to agroecology can provide healthy food by maintaining productivity, increasing soil fertility and biodiversity, and at the same time reducing the footprint of food production. Agroecology takes into account the hybridization of scientific knowledge with farmers' knowledge and integrates three dimensions: (i) one of a technical-productive nature, where ecology and agronomy converge in the design of agro-ecosystems;

(ii) a second dimension oriented to the cultural and socio-economic analysis of local agro-food systems from a territorial vision; (iii) a political dimension, whose priority objectives are to reinterpret the analysis of power in the agro-food system and to achieve food sovereignty. In order to respond to the scientific challenges, the paradigms inherent to the Circular Bioeconomy, product of a symbiosis between Ecology and Economy, are part of the guiding principles of Agroecology: to use renewable resources, to maximize efficiency in the use of biological resources. Within this, in particular, organic agriculture has great potential for farmers and consumers, minimizing, re-using and recycling waste as much as possible.

(iii) Both chemical fertilizers and pesticides have contributed to the pollution of soil, water and air, affecting the loss of biodiversity, harming non-target plants, birds, mammals, insects and amphibians. In addition, we must add the undoubted effect of climate change which has gradually led to an increase in the average global temperature, which together with the human impact on unsustainable practices and management of the environment, has considerably exacerbate desertification risk across the planet. For all these reasons, in order to ensure food supply and to adapt or protect ourselves from the effects of climate change, it is necessary to seek more efficient production systems benefiting natural resources and environmentally sustainable models that favour the saving of resources and have the lowest possible environmental impact. We must consider increasing organic agriculture, reducing the use of chemical fertilizers, decreasing the current dependence on pesticides and antimicrobials, improving animal welfare and reducing the loss of biodiversity that is taking place. We must also integrate new approaches provided by biotechnology and genetic improvement that allow a better use of plant and animal resources.

(iv) The greatest challenges currently facing biotechnology and plant breeding are climate change and population growth and both of them require the development of new plant varieties. While traditional improvement goals are still valid, i.e. higher yields, healthier products and resistance to multiple pests, new ones need to be added, such as adaptation to higher CO2 levels or high temperatures. To meet this challenge, advances in the biological sciences have provided us with powerful data collection techniques, high-throughput “omics” technologies supported by bioinformatics approaches of unprecedented capacity, and innovative biotechnology tools, in particular genome editing and synthetic biology. Using these technologies in model and crop plants, and exploiting the untapped local genetic variability, will allow us to boost Biotechnology and Plant Breeding for the generations to come. The development of these new technologies must focus on obtaining new products to maintain food security and promote sustainable industrial uses of photosynthetic organisms.

(v) Each year, different harmful organisms (pests and pathogens) reduce the potential yield of agricultural crops by about one third and threaten the sustainability of the world's forests. The current scenario of progressive decrease of cultivable surface and increase of temperature and global CO2 of the planet contribute to the emergence and re-emergence of different invasive species of pests and pathogens with negative effects on forests, crops, biodiversity of these ecosystems, and animal and human health. It is essential to generate new knowledge and technologies for a more efficient control and management of strategic diseases and pests that are a threat in key productive sectors into the world economy and in particular the Spanish one.

(vi) On the other hand, animal production, both terrestrial and aquaculture, is key from an economic, social and environmental point of view. Moreover, it supports a powerful agro-food industry. Although its main objective is to produce food for human consumption, the sector faces important challenges: to increase the efficiency of production of food with high nutritional value and safe for human consumption; to ensure animal health and welfare; to reduce the environmental impact of animal production; to improve the quality of animal products and their traceability; to adapt production systems to the available resources and production purposes and to increase their resilience to social, economic and environmental changes on a global scale.

(vii) Population pressure and climate change are forcing food industry to use more sustainable processes to increase productivity and minimise environmental impact. In addition to the sustainability of primary production, there is a need to support these sustainable food systems by assessing the safety and effectiveness of innovation in the food chain. The food industry can find innovative ways to reduce the overexploitation of multiple species by optimising raw materials and promoting the use of waste and by-products. In addition, this industry must also be prepared to provide innovative products in a fast and reliable manner, flexible and even customizable to meet new consumer demands, such as specific health and even lifestyle requirements. This requires multidisciplinary studies on raw materials, waste recovery, efficient green technologies, new products and intelligent biodegradable packaging. Likewise, the globalization of food markets in the 21st century has posed new food safety challenges. The persistence and emergence of conventional and emerging primary food risks such as viruses, bacteria, parasites, allergens, harmful algae, fungi, toxic contaminants, among others, and the patterns of their corresponding foodborne diseases have become globalised, as in the recent pandemic caused by the severe acute respiratory syndrome coronavirus 2 virus (SARS-CoV-2). Successful initiatives to manage emerging risks must identify, assess and prioritize potential risks, as well as respond with sustainable strategies capable of reducing threats. This requires the development of accurate, sensitive and rapid detection methods for real-time process control. Quality, security and authenticity will depend on powerful process analytical tools, multiple sensors and advanced computing and digitizing systems.

Thus, this theme will work to address the main research issues for the development of environmentally and economically sustainable and socially accepted agricultural ecosystems, from the incorporation of the main technologies and results of basic and applied research in different fields of agricultural sciences, in close interdisciplinary collaboration with other scientific areas that address the study of natural resources and socio-economic processes and factors.

Therefore, this topic, responsible primary production, has been divided into 7 chapters that aim to describe the most relevant challenges in the medium and long term:

- Chapter 1: Agriculture and ecosystem services
- Chapter 2: Agroecology and circular bioeconomy
- Chapter 3: Comprehensive improvement of livestock and aquatic systems
- Chapter 4: Plant health. Resistance to pests and diseases
- Chapter 5: Biotechnology and plant breeding
- Chapter 6: Sustainable production in the food industry
- Chapter 7: Food Safety

Addressing the different challenges proposed will require not only the participation of the different CSIC research groups but also international collaboration and the creation of networks that will make it possible to develop common strategies when addressing these challenges. The CSIC has research groups of recognised international prestige that could lead the different initiatives that may arise from the implementation of these challenges. The incorporation of young postdocs and doctoral students should allow the renewal of new ideas in a CSIC staff that presents a high level of ageing. Similarly, we must make the CSIC attractive in order to attract researchers from other countries by facilitating the mechanisms of incorporation into our research system.

In this area, it is essential to have the collaboration of the different social and productive actors, farmers, aquaculturists, livestock breeders and the agro-food industry, in participatory processes that lead to consensual decisions that can favour the successful transfer of research results. Although the CSIC has long and extensive experience in collaborating with the Spanish food production sector, it will be necessary to increase interaction at different stages of the research process, in order to implement the scientific results obtained. The approach to the challenges proposed in this manuscript is in line with the European strategies for 2030 "*Biodiversity*" and "*Farm to fork strategy for sustainable food*" as part of the "*Great European Green Agreement*". The new "Climate Change and Food Security" programme is an ambitious response to the challenges of climate change in the food chain by proposing a transformation of primary food production towards more sustainable systems that allow the conservation of biodiversity.

76 researchers from 30 CSIC research centres have participated in the preparation of this book, with the collaboration of three universities and a private institution:

Instituto de Economía, Geografía y Demografía (IEGD)
Instituto de Recursos Naturales y Agrobiología (IRNAS)
Instituto de Agricultura Sostenible (IAS)
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Misión Biológica de Galicia (MBG)
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Estación Biológica de Doñana (EBD)

CHAPTER 1

ABSTRACT

Sustainable intensification and sustainable land management are needed to reconcile agriculture with the delivery of ecosystem services in a win-win situation. This requires:
(i) enhanced knowledge on agroecological processes to identify which practices work under different environmental conditions;
(ii) modelling and monitoring of key performance indicators for landscape scale assessments;
(iii) integrated cost-benefit analysis; and
(iii) upscaling of promising practices in coordination with stakeholders.

KEYWORDS

agro-ecosystems | sustainable intensification | ecosystem services | biodiversity | pollination | crop production intensification

CHAPTER 1

AGRICULTURE AND ECOSYSTEM SERVICES

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EXECUTIVE SUMMARY

Modern agriculture provides important resources and ecosystem services to society (e.g. food, fibre, fuel production and climate regulation), but sustainable agricultural systems also strongly depend on ecosystem services (e.g. pollination, water provision, nutrient cycling). The transition towards Sustainable Intensification (SI) of agriculture and the use of sustainable land management practices requires understanding the interactions and the delivery of ES between agriculture and natural ecosystems in a context of global change and a global economy.

Research has advanced considerably on short-term small scale testing of new ideas and practices to make agriculture more sustainable. However, many of these ideas have not reached their full potential for large scale implementation. A major challenge is to identify how agriculture can become more efficient and resilient to climate conditions and contribute to optimal delivery of ES under different scenarios. Four key challenges are highlighted: 1) Upscaling sustainable intensification; 2) Research infrastructures for monitoring, prediction, and early warning; 3) Belowground biodiversity; and 4) Integrated cost-benefit and multi-criteria analysis for policy support. These key challenges require long-term studies and landscape scale assessment to develop and calibrate agronomic, ecologic and economic models to improve our understanding and prediction capacity of the effectiveness of SI and sustainable land management practices. Research infrastructures where

field observations in Living Labs are integrated with remote sensing and modelling are fundamental to identify innovative practices. Particularly better understanding is needed of soil biodiversity and its functionality to maximize production and delivery of ES. Insufficient knowledge about the direct and indirect costs and benefits and externalities of agriculture versus SI form a major barrier for their large scale implementation. An integrated cost-benefit analysis is fundamental for farmers and for the design of policy support and economic instruments beyond subsidies.

These challenges require transdisciplinary research, co-design and collaborative implication of complementary disciplines in different research areas of CSIC. The involvement of stakeholders in all stages of research, connecting academia with productive agriculture sectors and policy makers, is crucial to reinforce innovative research with impact in the real world.

1. INTRODUCTION AND GENERAL DESCRIPTION

1.1. Introduction

Almost 80% of the global ice-free land is used for farming, ranching and forestry (Kremen and Merenlender, 2018), with impacts ranging far beyond the areas directly used for agriculture. Although agriculture includes production from farmland, forestry and livestock related activities, this chapter focuses on farmland and forestry. Challenges related to livestock activities are dealt with in Chapter 3 and to agroforestry in Chapter 2. Conversion of natural to cultivated land is currently one of the main drivers of land degradation, climate change, and biodiversity loss. On the other hand, recent evidence shows strong support that above and belowground biodiversity can enhance agriculture production through ecosystem services such as pollination, pest control and nutrient cycling (Bommarco et al., 2013), though uncertainty remains about effectiveness in specific situations (Tscharntke et al., 2016). Moreover, there is increasing evidence that sustainable land management practices can help in the fight against land degradation, climate change and biodiversity loss. The challenge is how to reconcile agricultural production with biodiversity conservation and delivery of other ecosystem services in a win-win situation. Sustainable intensification[1] (SI) of agriculture provides solutions for example by maximizing the opportunities of agriculture landscapes to maintain biodiversity, while using this biodiversity to optimize food production. SI is defined as a series of interventions enhancing "the output of agriculture production while at the same time increasing the efficiency of natural, physical, financial and human resource investments and reducing negative environmental and social impacts" (Pretty and Bharucha, 2014). How to implement such a transition is an enormous challenge that requires the joint effort of agronomists, ecologists, economists and social scientists.

There is a growing awareness that agriculture produces much more than just crops (Dale and Polasky, 2007), and that we need to consider many other aspects of agriculture related to the protection of biodiversity and other ecosystem services (Post-2020 Global Biodiversity Framework) in a context of developing the rural environment (Cork 2.0 Declaration, 2016). Agriculture forms part of socio-ecosystems that require a holistic perspective. However, since the green revolution, emphasis in research on agriculture has

1. …*"producing more from the same area of land while conserving resources, reducing negative impacts on the environment and enhancing natural capital and the flow of ecosystem services"* . FAO (2011) Save and grow. A policymaker's guide to the sustainable intensification of smallholder crop production. FAO, Rome, 102 pp. http://www.fao.org/ag/save-and-grow/

been on optimizing production. While this has boosted the food production potential of the agriculture sector and reduction of hunger, it has also led to large scale degradation of ecosystems with negative impacts on nature and society (e.g. GHG emissions, human and soil health, contamination and overexploitation of soil and water). Future projections suggest that in the absence of technological changes and mitigation measures, the negative environmental effects of the food system could increase by 50-90% between 2010 and 2050 due to changes in population and income levels. Environmental impacts would thereby reach beyond levels that define a safe operating space for humanity, and so urge for action through innovation and mitigation in agriculture (Springmann et al., 2018).

Agriculture is central to many global challenges which include feeding the growing world population, producing high quality food and other products, maintaining landscape diversity, providing a stable and fair income to the rural population, and contributing to the conservation of biodiversity, and to climate change mitigation and adaptation. The combination of these challenges asks for a sustainable intensification in agriculture and recognition of the interactions between agriculture and natural ecosystems. SI has been propagated as a way forward to create a potential win-win situation for the agriculture and environmental sectors and allow progress towards multiple Sustainable Development Goals (SDG). The sustainable intensification of agriculture systems offers synergistic opportunities for the co-production of agricultural, social, and natural capital outcomes (Pretty et al., 2018). Optimization of the different functions of agriculture and its interactions with natural systems to support biodiversity and ecosystem services, requires increased efficiency, substitution of resources, redesign of the production system, and an integrated land use planning to minimize negative impacts at the landscape and basin scale.

To identify opportunities for a transition towards sustainable intensification of agriculture, we need to understand the interactions and the delivery of ecosystem services between agriculture and natural ecosystems. Ecosystem services (ES) refer to the direct and indirect contributions of ecosystems to human wellbeing, such as provisioning (of resources), regulating (useful ecological processes), supporting (to maintain biodiversity) and cultural (the non-material benefits) services. Agriculture contributes to ecosystem services, and natural ecosystems provide crucial services to agriculture. The main challenges in research relate to the identification of technical, social and economic solutions that help optimizing agriculture production and the delivery of ecosystem services from agriculture and natural systems based on synergistic solutions.

1.2. Agriculture & Ecosystem Services

Agriculture is strongly interlinked with provisioning, regulating, supporting and cultural ecosystem services. First, agriculture supplies a range of provisioning services especially related to the production of food, feed, fibre, fuel and raw materials like wood and biodynamic compounds (e.g. latex, oils, hormones) for all kinds of industrial purposes. But at the same time, agriculture receives a broad range of provisioning, regulating and supporting services from natural systems like the provision of water and genetic resources, pollination, and pest control, which are crucial for agricultures' production service capacity.

Second, agriculture has a direct impact on various regulating ecosystem services, especially in relation to regulation of climate, water quality and quantity, and prevention of natural hazards like soil erosion and flooding. Typical examples of potential regulating ecosystem services from agriculture are regulation of climate by reduction of greenhouse gas emissions and improvement of sequestration of organic carbon in soils and vegetation. Agriculture can also help prevent natural hazards, like floods and soil erosion, by optimizing vegetation cover and soil water retention capacity. On the other hand, agriculture is dependent on and can affect key regulating services such as pollination and pest control. About 75% of the cultivated crops depend to some degree on animal pollinators to maximize its production (Klein et al., 2006), and natural ecosystems control potential pests of crops and carriers of disease to human beings (Dainese et al., 2019). This is also emphasised by the new concept of One Health, which stresses the direct relationship between healthy ecosystems, biodiversity, and human health. The type of agriculture, i.e. the farming system, and the management practices largely determine if the impact on these regulating services is positive or negative. Capitalizing in ecosystem services, for example through sustainable intensification, could therefore reduce the need of chemical inputs, enhance yield stability and optimize ecosystem services to society without penalizing the economic return.

Third, agriculture has a direct impact on supporting services related to biodiversity. Habitat destruction, agricultural landscape simplification, and improper use of agrochemical inputs can negatively affect many species populations. However, many taxa can persist and even thrive in human-altered landscapes, and agroecosystems can also contribute to the maintenance of above and belowground biodiversity. Once more, the interplay between landscape heterogeneity, spatial and temporal crop diversity, management and use of agrochemicals, determines the opportunities to maintain the supporting services.

Finally, agriculture is also delivering cultural services, as it is an integral part of our culture. Cultural services include immaterial assets like traditional knowledge and more tangible representations of cultural heritage, like man-shaped rural landscapes. Currently, agriculture is facing a decrease of the agriculture workforce and particularly a lack of young farmers resulting in the loss of local knowledge. Changes of historical contexts have affected agriculture cultures and landscapes, and present agriculture exploitations, land use and territory occupation can often be traced back to the transformative process forced by technical changes or other drivers. This agriculture knowledge and resources approach provides a continuum to contextualize agriculture as a cultural service. Additionally, agriculture landscapes have an aesthetic component which attracts tourism and forms part of the cultural services provided by the rural areas. Farmers and foresters should therefore be valorized and reinforced as providers of cultural public goods and services through the protection of cultural and aesthetic values.

A major scientific challenge is to better understand and quantify the impacts of specific agriculture management strategies on crop production and other ecosystem services. This has been highlighted in numerous studies related to different ES such as biodiversity (Mendenhall et al., 2014; Torralba et al., 2016), reduction of diffuse pollution (Pavlidis and Tsihrintzis, 2018), carbon sequestration in soil and above-ground biomass (Feliciano et al., 2018), or pest control (Tscharntke et al., 2016). This uncertainty reflects gaps in knowledge, and hinders the expansion of best management practices and integrated systemic approaches, and creates uncertainty in the definition and monitoring of agriculture and environmental policies that support implementation of certain sustainable management practices in agriculture.

1.3. Agriculture in the context of global change

Agriculture and the delivery of ecosystem services must be assessed in a context of global change and a global economy. Its study requires consideration of interactions with future socioeconomic and climate scenarios. These scenarios will likely change the food demands, types of crops and planting seasons as well as crop yields around the globe and the effectiveness of sustainable land management practices. One of the best assets against the ongoing changes we are experiencing is relying on biodiversity (genetic, crop, and wild diversity) as insurance (Yachi and Loreau, 1999), and developing agriculture management that optimizes food production while contributing to climate change adaptation and mitigation. Tools and properly calibrated models as well as field and laboratory experiments are required to explore and identify the best management in different scenarios.

The risk of mismanagement will increasewith climate change effects and with increasing pressure on natural resources and food supply. In many areas, impacts of climate change are already evidenced, for example by increased temperatures causing shifts in the timing of biological processes, or increases in the frequency and intensity of droughts leading to crop failure. The Mediterranean region has been identified as one of the most affected global hotspots for climate change, which is already manifested by faster increasing temperatures than the global mean and significant decreases in annual precipitation. Climate change scenarios project worse conditions, particularly in the Mediterranean semi-arid regions, for which less and more erratic rainfall and higher temperatures are envisaged, leading to higher plant water stress, increased rates of soil erosion, and higher flood risks. In contrast, in many temperate regions, higher annual precipitation is expected with more extreme weather and lower summer rainfall, potentially leading to more floods, and water shortage in summer months.

Spain is one of the largest agriculture exporters in the European Union, the agri-food sector is one of the most dynamic sectors of the Spanish economy, and half of all land in Spain is used for diverse agriculture or livestock activities. The range covers from competitive intensive systems that regularly update their technologies, to extensive rainfed agriculture that is largely dependent on rainfall for being productive. Unsustainable land management practices in all types of agriculture have negative impacts on soil and water resources (quantity and quality), and on biodiversity. Nevertheless, driven by increasing international public concern about sustainability and market demand for sustainable produce, there are emerging examples of agriculture systems moving towards more sustainable management, e.g. by using cover crops in tree crops, crop rotations, and integrated (biological) pest management, leading to better protected ecosystem services, and contributing to climate change mitigation and adaptation.

Although increasing international competition will change the agriculture sector, intensive agriculture will remain a major socioeconomic sector for our country. We can distinguish two main intensive agriculture systems with maximum impact on biodiversity: a) irrigated woody crops, such as olives, vines, almonds, citrus, peaches, b) horticultural crops of high value like strawberries, lettuce, broccoli, onions, asparagus, melon, etc. These systems have in common that they usually require irrigation and they often have negative environmental impacts due to their high demand for water and agrochemicals. The environmental problems caused by unsustainable agriculture are well-known already for decades without a clear improvement despite incremental regulations (e.g. CAP conditionality, Water Framework Directive, agro-environmental measures). The extensive cereal-based systems, particularly when rotated with a spring crop, are often associated with intensive soil preparation, soil degradation and severe water erosion due to prolonged periods with bare soils. Adoption of conservation agriculture has been proposed to reduce this impact but so far its adoption in Europe and in Spain is very low. To achieve an effective sustainable intensification of agriculture and an optimal contribution of intensive and extensive agriculture to deliver ecosystem services, there are several challenges to be addressed in the medium/long-term for which CSIC is uniquely positioned as is further explained in sections 3 and 4.

2. IMPACTS OF SCIENTIFIC PROGRESS AND POSSIBLE APPLICATIONS

While agriculture benefits from healthy and diverse environments, unsustainable land management practices have often resulted in land degradation and loss of biodiversity. In contrast, sustainable land management practices can contribute significantly to global challenges such as the fight against climate change, land degradation, and loss of biodiversity. To optimize these multiple benefits requires a transition to sustainable intensification and strengthening of the role of agroecosystems in delivery of ecosystem services. Besides the provision of ecosystem services, sustainable intensification aims at integrating food production of high quality and market viability with optimum protection of natural resources and ecosystem services, crucial for human well-being. This requires a basic science perspective to construct simple models that capture the complexity of multifaceted systems. To find sustainable solutions in agriculture production, requires integration of ecological models with economic cost-benefit analysis and agronomic crop-production models. While the three fields have already advanced significantly in understanding individual parts of the puzzle, there is an urgent need for integrated transdisciplinary studies and assessments.

What progress beyond the state of the art can we expect from research?

1. Quantification and optimization of the use of water and nutrients by different crops and other elements of the food chain in agricultural systems in order to increase water and nutrient use efficiency and prevent contamination of surface and groundwater. Although extensive research and progress have been made on this topic, basic knowledge in this regard is still limited (Wu et al., 2016). Particularly, models need to be evaluated and redesigned to cover trade off effects and long term effects, and must be properly calibrated for local conditions.
2. Integration of ecological theory with crop management beyond the crop field, especially with its interaction with ecosystem services and biodiversity at the landscape level.
3. Reduction of uncertainty in determining the ecological and economic impact of different management practices on the provision of ecosystem services; and identification of robust indicators for evaluating and monitoring these practices at different scales.

Sustainable intensification is usually envisioned for systems that apply a high amount of pesticides and fertilizers for two reasons. First, these systems are, usually, the ones with the technology and economy of scale to introduce the changes required. Second, this high use of inputs has exacerbated environmental problems in the last decades, e.g. decrease of biodiversity and overexploitation and contamination of surface and groundwater. Extensive cropping systems are commonly associated with high soil erosion rates and loss of soil organic matter content due to frequent tillage, e.g. in tree crops and cereal-oil cropping systems. Some aspects of SI can also make these extensive systems more efficient and productive. In addition, by implementing sustainable land management practices, extensive cropping systems have very high potential to contribute to the delivery of ecosystem services, climate change mitigation and adaptation and protection of biodiversity. Restoration of these extensive systems also contributes to revitalization of rural areas, as discussed in detail in Chapter 1.

Potential applications in society of the research findings related to sustainable intensification and sustainable land management are:

1. Increased efficiency in management of existing agriculture systems making better use of water, soil and nutrient resources, as well as animal provided ecosystem services such as pollination and pest control. This will increase cost-effectiveness and international competitiveness of the agriculture sector.
2. Foster large scale implementation of SI and sustainable land management practices through better insight about their impacts under different environmental conditions.
3. Scientific underpinning of agriculture policies towards a green economy and the monitoring of their impact.

Altogether, research and progress on the key challenges related to agriculture and ecosystem services will support better governance of the agriculture sector, providing scientifically-sound information for well-informed policy development (i.e., more suitable and targeted policy instruments promoting a balanced economic-ecological performance of agriculture activity) and for farmers' decision-making (i.e. implementation of new and local-adapted agriculture practices improving economic and environmental farm performance at the same time).

3. KEY CHALLENGES

Global agriculture faces enormous challenges due to the growing population, climate change, land degradation, biodiversity loss, and a more competitive agriculture in a global economy. In the coming decades, these processes will have serious implications for soil and water resources, and for many essential ecosystem services, such as the production of food, fiber and fuel, the supply of sufficient and clean water, erosion and flood control, and climate regulation (Dominati et al., 2010; Schulte et al., 2014; Swinton et al., 2007). Sustainable land management practices in intensive and extensive agriculture systems are essential to face these challenges, due to their potential to increase production, protect natural resources, increase the resilience of agro-ecosystems, and minimize greenhouse gas emissions. These solutions have to consider the climate, water, energy, food nexus.

Research has advanced considerably on short-term small scale testing of new ideas and practices to make agriculture more sustainable. However, many of these ideas have not reached their full potential for large scale implementation. Some examples of such practices are vegetated strips for soil erosion and flood control, the use of cover crops in tree crops in semiarid areas, conservation agriculture in annual crops, crop diversification in space and time, integrated nutrient and pest management, increased water use efficiency and circular production systems, or pollinator friendly practices to increase pollinator populations. The uptake of these and other practices requires a detailed evaluation of the impact and tradeoffs on ecosystem services at commercial scale, and integrated cost benefit analysis that shows its potential to farmers and to policy makers, especially in the long term.

There is urgent need to advance our knowledge of how intensive and extensive agriculture can become more efficient and resilient to future climate conditions and contribute to optimal delivery of ecosystem services. One of the key challenges is how to foster large scale implementation of Sustainable Intensification and sustainable land management in intensive and extensive systems particularly at commercial scales. This requires transdisciplinary research, co-design, co-innovation and coordinated actions at the landscape level, including monitoring systems to provide early warning signals. The involvement of stakeholders in all stages of development of innovative agriculture practices through well designed stakeholder participation, connecting academia, the agriculture sector, and other stakeholders is needed to guide innovative research with impact in the real world.

At a more detailed level, past research has provided insight on sustainable crop management and aboveground ecosystem services. There is still a lack of knowledge regarding the role of belowground biodiversity and ecological processes for ecosystem service provision.

3.1. Upscaling sustainable intensification (SI) and sustainable land management

There are many potential solutions in agriculture to feed the growing world population while protecting biodiversity and contribute to other ecosystem services, but we lack the knowledge to identify which solutions can be scaled up both technically and logistically, how they depend on local environmental and socioeconomic conditions, and how they cause synergies and trade-offs. There is also a lack of prediction capacity of the effectiveness of SI and sustainable land management practices under current and future climate conditions using agronomic, ecologic and economic models. Specifically designed long-term field research is needed to improve and calibrate these models and study the evolution of soil related ecosystems services. So, to allow upscaling of SI and sustainable land management practices in intensive and extensive farm systems, there is a need for further research regarding which practices work best under different current and future environmental conditions and scales. This reflects the complexity of agroecosystems and the diversity of possible responses, or even the non-applicability of proposed practices at commercial level.

There is a particular need for further agro-technological innovation to maintain or increase crop yields while making more efficient use of inputs of water, nutrients and agrochemicals, and reducing losses leading to contamination of soil and water. These technological innovations range from the development of information systems using UAVs[2] to optimize fertilizer application, to development of drought resistant crops, circular production systems, reusing (waste) water, use of renewable energy and biomass, integration of crops with photovoltaic energy production, and crop diversification in space and time. For extensive farming systems, there is need to identify which low cost practices are most effective under different environmental conditions to maintain or increase crop yield, enhance soil quality, increase above and belowground biodiversity, and contribute to climate change adaptation and mitigation.

Most research regarding SI and sustainable land management focused on individual techniques at plot level. There is still a lack of knowledge at the farm and landscape level (e.g. small catchments), which are the most relevant for policy making, and because certain processes and interactions operate at landscape scales (e.g. water regulation, pollinators). Assessments at the landscape scale provide proper appraisal of opportunities to enhance delivery of ecosystem services. For example, the development of a mosaic pattern by combining heterogeneous cropland and natural vegetation in interstitial spaces among farm plots and a landscape-scale matrix of habitats to increase the stability of agricultural production systems and provide system resilience. In this context, new methodologies are needed to assess the effectiveness of implementation of agro-environmental measures at landscape level that allow to integrate this knowledge in spatial land use planning to optimize the delivery of ecosystem services. Well characterized robust indicators are needed to evaluate the economic, environmental and social impacts and considering the climate, water, energy, food nexus. Coordinating landscape interventions, often including lands owned by multiple land owners and by the public administration, is only possible by involving and co-designing the intervention with all stakeholders. Top down imposed strategies will fail, even

2. Unmanned Aerial Vehicles (UAV)

when well planned, if social, economic and cultural aspects are not taken into account. This stresses the need for multidisciplinary multi-scale research consortiums to address these complex socio- agroecosystems.

Advancing research on this key challenge will have particular impact by providing:

1. Practical examples of agro-technological innovations, sustainable land management practices, and integrated land use planning that provide synergistic opportunities for the production of agriculture, social, and natural capital outcomes in intensive and extensive farming systems.
2. A detailed inventory of the impacts and tradeoffs of large scale implementation of SI and sustainable land management practices on ecosystem services under a range of present and future environmental and socioeconomic conditions. The inventory reports on environmental, economic and social key performance indicators from local to regional scales. This information is of direct relevance for farmers and to support policy development to foster the adoption of SI and sustainable land management practices that optimize the delivery of ecosystem services.

3.2. Research Infrastructures for monitoring, early warning and prediction

To optimize the delivery of ecosystem services from agricultural and natural habitats, we must overcome the barriers for the implementation of SI and sustainable land management practices in intensive and extensive agriculture. A major barrier for implementation is the uncertainty associated with ecosystem services delivery for a particular place and time. While we know that in some cases ecosystem services can substitute for external inputs, it is hard to predict in which situations ecosystem services will not cover the crops needs. Implementing affordable and user friendly monitoring systems that produce near term forecasting in commercial conditions, based on robust models, may facilitate the use of sustainable agriculture practices to minimize the use of external inputs, with an early warning system that acts as a safety net in case a particular place or time is e.g. too dry, lacks pollinators, etc., and requires additional measures or external inputs to complement the ecosystem service delivery.

To design best management practices, there is a strong need for more knowledge and multidisciplinary knowledge exchange regarding the impacts and dependence of agriculture on ecosystem services under different environmental conditions. Moreover, to be prepared for the future, we need to be able to predict the effects of future environmental conditions on agriculture and on related ecosystem services. One promising avenue that may be possible thanks to the increased trend in monitoring agroecological systems is the identification of early warning signals that allow us to act before negative consequences are already in place (Kefi et al., 2014). To make this operational in agriculture, we need to identify key sustainability indicators that facilitate evaluating the impacts of SI and sustainable land management practices.

This challenge requires the development of a large Research Infrastructure (RI) that includes the long term experimentation required to observe the effects of various management options, for example, those improving soil biodiversity, soil quality and carbon sequestration, or those dealing with the effects of crop rotations. A RI for monitoring, early warning, and long-term data collection will improve the prediction of the impacts of agriculture on ecosystem services and the status of delivery of ecosystem services to agriculture. The RI should combine 1) monitoring through remote sensing based indicators with, 2) modelling impacts under future climate change scenarios, and 3) a network of Living Labs, in line with the current proposals developed by the EU Mission for Soil Health and Food (Veerman et al., 2020), in which experiments are developed and monitored in close collaboration with stakeholders to facilitate knowledge exchange regarding best practices and financial, technical, cultural, and knowledge constraints for implementation. The RI will also facilitate data sharing between scientists and with policy makers regarding research findings and new research needs.

Advancing research on the key challenge of Research Infrastructures will have particular impact by providing:

Unprecedented ability to monitor, and accurately predict the effects of different agriculture management practices and the impacts of global environmental changes on the delivery and exchange of ecosystem services between agriculture and natural environments. This continuous flow of information will facilitate the selection and implementation of tailor-made agriculture practices fit to local environmental and sociocultural conditions to optimize the delivery of ecosystem services, and help adjusting the agriculture sector to external stressors due to environmental change.

3.3. Belowground biodiversity

Soil biodiversity comprises all micro- and macro-organisms living in and on soil ecosystems, both above and belowground. Micro-organisms such as bacteria, archaea, fungi, protozoa, microalgae, etc., are a major workforce responsible to maintain a healthy and productive soil. The huge microbial diversity held by soils is responsible to carry out critical ecosystem functions (Whitman et al., 1998). Microbes are able to fully mineralize organic matter (including highly complex and recalcitrant compounds and polymers) down to CO_2 and complete the cycling of nutrients and elements. Among macro-organisms living in soils are insects, arthropods, earthworms, nematodes. Soil organisms contribute to maintaining soil structure, composition and functionality and are ultimately fundamental to sustain terrestrial ecosystems.

There is currently a need for better understanding of the role of soil biodiversity in relation to SI and sustainable land management practices. Most urgent questions relate to how soil biodiversity is associated with soil physical, chemical and biological properties, processes and ES and which practices contribute to restoring, maintaining and improving soil biodiversity (Truchy et al., 2015).

Crop production must be balanced with a maintenance of soil biodiversity to achieve sustainable agriculture systems. Large scale monocultures in agriculture have been reported to reduce biodiversity, whereas a sustainable agriculture requires the presence of high biodiversity to warrant soil health. Thus, sustainable agriculture is based on preserving biodiversity and the ecosystems gain from maintaining its diversity. This bidirectional relationship between agriculture and biodiversity must be well understood to achieve a functional and sustainable agriculture. Research should focus on better understanding the soil macro- to micro-organisms and its functionality and interactions between functional diversity and environmental change (e.g. climate warming, land use change).

A major challenge for the next decade is to identify and characterize adequate soil biodiversity indicators to be used for rapid and unambiguous assessment of soil health and delivery of ecosystem services. Different soil types and different uses of soils need to be analyzed to determine the influence of soil biodiversity and specific species or microbial groups with distinctive functions. The new knowledge regarding the role of biodiversity for soil health and the soil functional indicators are fundamental to identify and understand most effective sustainable agriculture practices.

What do you get with this challenge?

1. Detailed understanding of the link between soil biodiversity, crop functioning and delivery of ecosystem services. Advanced insight for recommendations (farm level) about what agriculture practices may

support or detract soil biota and their performance, and the relative importance of different soil biota for various ecosystem services, environmental and human health and well-being.

2. A series of indicators of soil health based on soil biodiversity for rapid soil assessment and evaluation. These indicators will be useful for policy makers and land owners to assess soil environmental status, similar to the way indicators are used in the European Nitrates or Water Framework Directives.

3.4. Integrated cost-benefit and multi-criteria analysis for policy support

The quantification of the impact of specific management and land use practices on ecosystem services remains highly uncertain (e.g., Winter et al., 2018), which restricts the development of policies to encourage implementation of sustainable intensification and sustainable land management practices. To counteract these uncertainties we need an integrated economic appraisal of their costs and benefits, including direct and indirect costs and benefits and accounting for positive and negative externalities. Once we have better estimates of the impacts, costs and benefits of alternative agriculture management practices, we need guidelines and decision support tools based on multi-criteria analysis to help decision makers analysing the implications of their decisions.

Agriculture is a multifunctional activity involving benefits and costs for farmers and for society (externalities). Traditionally, only private benefits (production) and costs (farming expenses and investments) have been assessed when analyzing changes in agriculture practices, considering that only those practices increasing farmers' profit are worth to be considered for implementation. However, ignoring public benefits (wealth and employment generation, vitality in rural areas and positive environmental changes, or climate change mitigation and adaptation) and costs (negative environmental changes: pollution, erosion, biodiversity loss, landscapes degradation, climate change, etc.) has led to myopic decision-making that has involved welfare losses. That is, the changes in agriculture practices have led to private profits in the short run, but in many cases, these profits have been accompanied by large public losses generated because of environmental damage. This is the reason why recent evolution of farming activities has led to increased social concern in many regions.

The phenomena above-mentioned is known in economic terms as "market failure", caused by the existence of agriculture non-commodities outputs (externalities). This problem generating welfare losses can be solved by government intervention through a wide set of policy instruments, from command-and-control mechanisms (i.e. agrochemicals prohibition, regulatory requirements, etc.) to economics incentives (conditionality of direct payments, agri-environmental programs, environmental taxation, etc.). The private sector and business community can also help implementing sustainable agriculture through initiation of sustainable business models that reduce environmental impacts and internalize the environmental costs and benefits. In order to select effective policy instruments or business models requires accurate assessment of benefits (environmental improvements) and costs (production losses and increased production costs) associated with each alternative. Only if this information is available, policy-makers and business leaders will then be able to verify that implementation is optimum from a welfare and business improvement point of view .

Although there is a plethora of scientific research in valuing non-commodities output from farming activities, several main problems are jeopardizing that the information generated could be used for policy-making and business model development. Most of the research is focused on one environmental issue only (erosion, or water pollution, or biodiversity loss) for a local-specific agro-ecosystem. Of course, this approach is accurate from a scientific point of view, but information requirements for policy-making need more integral (i.e. considering all environmental issues related to farming activities) and general (i.e. information valid for large enough geographical units) assessments. Furthermore, most research provides results measured in physical terms only (i.e. tons of CO_2, tons of soil erosion, mg of N per liter of water, etc.). These results need to be translated into monetary terms (economic valuation) to allow analyzing trade-offs among the different environmental externalities and agricultural production. The main mid-long term research challenge is to provide integrated cost benefit analysis and multi criteria analysis of sustainable agriculture alternatives from farm to regional and national scales and to identify which economic instruments beyond subsidies are most suited to promote large scale implementation of sustainable agriculture.

Advancing research on this key challenge will have particular impact by providing:

1. Innovative methodologies to assess and compare all direct and indirect costs and benefits of SI and sustainable land management practices, including positive and negative externalities.

2. Increased insight into the actual costs and benefits related to the implementation of SI and sustainable land management practices, including positive and negative externalities.
3. This challenge will be particularly relevant to support practical (regional and international) policy and sustainable business development and will contribute to an effective science-policy and science business dialogue, in which research institutes and their staff will be involved in policy and business development and ex-post evaluation. The enhanced science-policy and science-business dialogue will establish a bi-directional communication which facilitates better informed decisions by policy makers and business leaders and helps in the identification of policy and business relevant research opportunities to develop new research with impact in society. It is suggested that every research project financed with public funds provides a specific final report regarding policy implications of the knowledge generated, pointing out how the results obtained could improve policy-making and which policy-makers should be aware and informed about the research outcomes.

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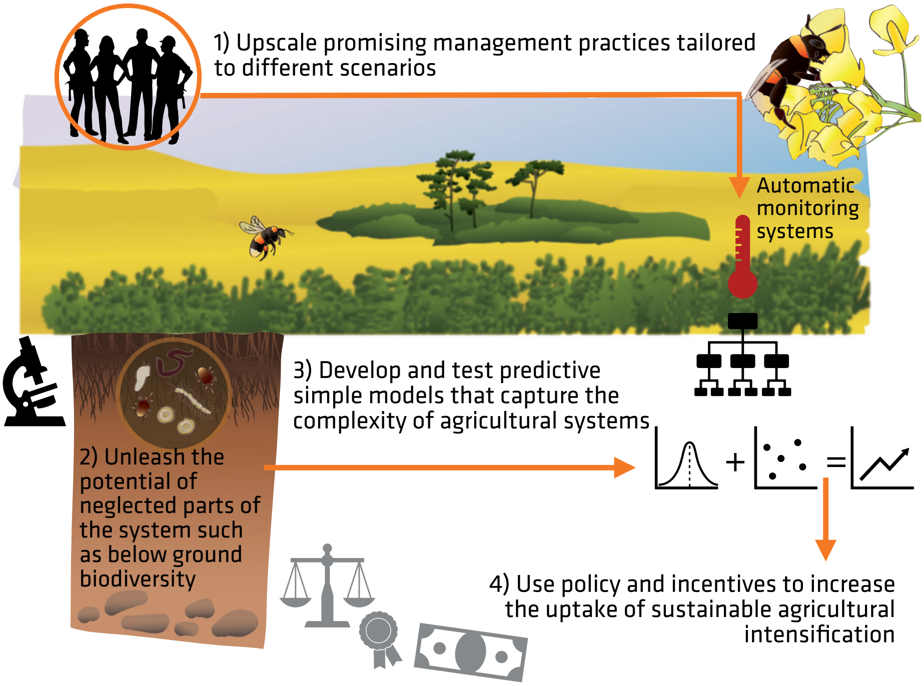
ANNEX 1

ANNEX 1. Additional photographs: Examples of some of the typical Spanish rainfed farming systems.

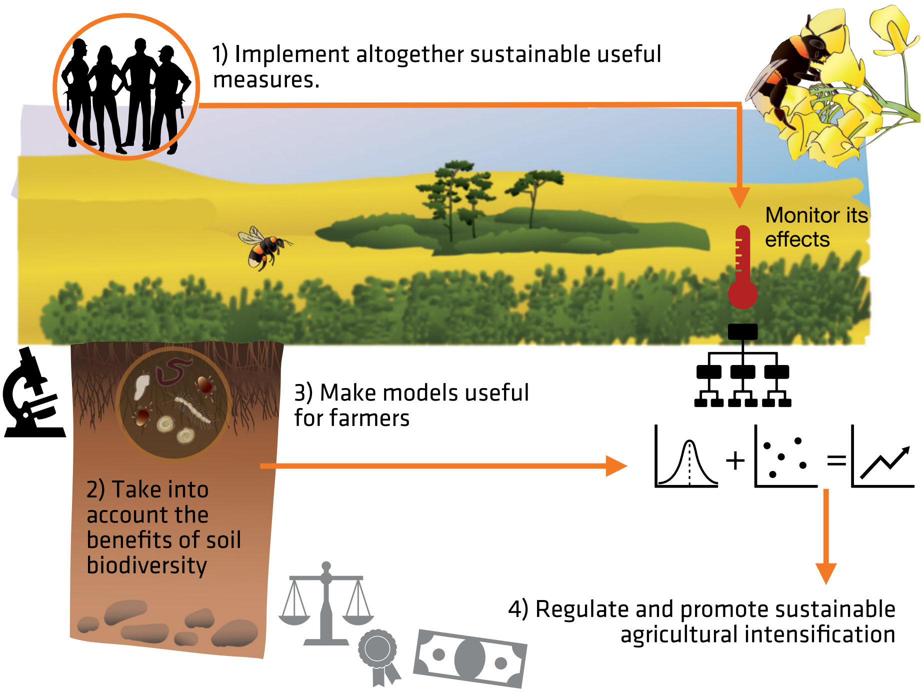
SUMMARY FOR EXPERTS

Sustainable Agricultural Intensification:



SUMMARY FOR THE GENERAL PUBLIC

Sustainable Agricultural Intensification:



CHAPTER 2

ABSTRACT

Results provided by a panel of experts reveal that some of the vital challenges facing Agroecology in the near future involve its contribution to Climate Action, to increasing biodiversity or to the co-creation of knowledge by researchers and farmers, as well as the application of criteria of Circular Bioeconomy to agro-food production and distribution. Other noteworthy challenges refer to the design of agroecosystems at landscape scale or the creation of agroecological local food systems enabling an upscaling of production and consumption.

KEYWORDS

agroecology | agroecosystems | agricultural landscapes | climate action | biodiversity | circular bioeconomy | co-creation of knowledge | local agro-food systems | upscaling

CHAPTER 2

AGROECOLOGY AND CIRCULAR BIOECONOMY

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EXECUTIVE SUMMARY

Agroecology involves a transdisciplinary scientific approach that attempts to conduct holistic research of the interrelations among the agronomic, biophysical, ecological, social, cultural, economic and political components of agroecosystems. It integrates three dimensions, as a research discipline: (i) the first of these is of a technical-productive nature and focuses on the design of agroecosystems, with Ecology as a scientific reference framework and in harmony with peasant knowledge; ii) a second dimension addresses the cultural and socioeconomic analysis of the agro-food system from a territorial perspective; and iii) a third political dimension, food sovereignty, attempts to reinterpret the analysis of power (economic, decisional, etc.) in the agro-food system. The Circular Bioeconomy, which results from a symbiosis between Ecology and Economy, adopts a series of principles that it shares with Agroecology: using renewable resources, maximising efficiency in the use of resources and maximum possible reutilisation of waste.

A methodology produced by a panel of experts specifies and defines the challenges to which Agroecology and the Circular Bioeconomy must respond in the near future. These challenges are classified in six main axes: i) the design of sustainable agroecosystems at landscape scale; ii) Agroecology and Climate

Action; iii) Circular Bioeconomy in agro-food systems; iv) Agroecology and promotion of biodiversity; v) co-production and dissemination of agroecological knowledge; vi) agroecological local food systems and upscaling.

There exists a need to promote the transdisciplinary confluence of researchers specialised in the different areas pertaining to the Environmental, Agronomic, Food and Social Sciences, in order to address the current socioeconomic and environmental issues relating to agriculture and sustainable food production. At the present time, the CSIC avails of no institute or department specialised in Agroecology or in the Circular Bioeconomy, following the disappearance in 2010 of the Agroecology Dept. of the former Centre of Environmental Sciences of Madrid. Nonetheless, with regard to the challenges put forward, the institution does avail of groups and experts in different fields who could work in coordinated research teams in Agroecology and the Circular Bioeconomy, if a nexus were to exist for scientific articulation at the platform, programme or project levels.

1. INTRODUCTION AND GENERAL DESCRIPTION

Agroecology involves a transdisciplinary scientific approach that attempts to investigate in a holistic manner the interrelations among the agronomic, biophysical, ecological, social, cultural, economic and political components of agroecosystems. Agroecology attempts to analyse agro-food activities from an ecological stance, but it also provides a transversal vision to the analysis of local agro-food systems, which interrelates several different disciplines belonging to the agronomic, environmental and social sciences.

Agroecology, as a research approach, integrates three dimensions (López and Álvarez, 2018): (i) the first of these is of a technical-productive nature and focuses on the design of agroecosystems, with Ecology as a scientific reference framework and in harmony with peasant knowledge; ii) a second dimension addresses the cultural and socioeconomic analysis of the agro-food system from a territorial perspective; and iii) a third political dimension, food sovereignty, attempts to reinterpret the analysis of power (economic, decisional, etc.) in the agro-food system.

Apart from constituting a scientific approach, Agroecology involves the application of a series of practices aimed at sustainable growth and production of foodstuffs, and at constituting a social movement that demands better objective conditions for farmers (and small rural agro-industries) and attempts to make sustainable and healthy food a basic right of all citizens. This triple vision, as a discipline, a combination of agro-food practices and a social movement, is broadly covered in the literature (Wezel et al., 2009). This vision clearly promotes the eminently empirical nature of learning in Agroecology, which, as a specific disciplinary feature, results from the hybridisation between peasant knowledge and scientific knowledge.

The international literature defines a series of principles to which agroecological practices must respond (Altieri, 1995; Gliessman, 2015; Guzmán et al., 2000; Nicholls et al., 2015). The increase in functional biodiversity of agroecosystems strengthens their “immune system”, making them more resilient to changing patterns of precipitation and temperature. Based on the principle of closure of biogeochemical cycles, improvements in biomass recycling and soil fertility also constitute key elements in agroecological praxis, for which there is a need to optimise the decomposition of organic matter, recycling of nutrients and balance of moisture occurring in agriculture and livestock farming. Conservation and enhancement of genetic resources, energy, nutrients and water is essential for the sustainable functioning of agroecosystems. Promoting the biological interactions and the synergies existing between the components of agricultural diversity constitutes another fundamental principle of agroecological farming. Another objective involves a drastic reduction of external inputs and energy dependence, which means that producers start by reducing their level of economic vulnerability.

With regard to the principles governing practices other than those relating to farming (commercial, organisational, etc.), agroecological initiatives usually involve marketing in commercially and geographically short chains, in an attempt to reduce the large amount of materials and non-renewable energy consumed by the current food system, which is largely based upon long-distance food chains. Promoting reconnection between producers and consumers has always been a priority in the ideology of agroecological experiences: farmers' wellbeing is considered to constitute an attribute in consumers' preferences. Local agroecological initiatives tend to adopt models of flexible organisation, proposing a functioning that responds to criteria of self-organisation, participatory democracy and bottom-up decision-making systems. Other common features of many agroecological experiences involve promoting links with the local culture or creating local networks for dissemination of knowledge among producers, consumers, activists and academics.

Bioeconomy, as a scientific approach resulting from a certain symbiosis between Ecology and Economy, makes a significant change in the economic paradigm because, rather than exclusively optimising competitiveness or company profitability, it prioritises conservation of biological resources beyond the production cycle itself, as well as ecological optimisation in the use of resources. This discipline aims to study the series of economic activities that make use of biological resources as basic elements: this includes agriculture, forestry, fisheries, food production and paste and paper production, as well as certain parts of the chemical, biotechnological and energy industries. Consequently, a significant segment of the bioeconomic activities involves agriculture and livestock farming, forestry or food production. A governing principle of Bioeconomy entails replacing fossil-based materials and energy with renewable alternatives, a concept fully incorporated into the agroecological paradigm.

Furthermore, the Circular Economy attempts to reduce consumption of resources by promoting a more efficient use of materials and energy through reuse and recycling of waste. Agroecology aims to close cycles at a maximum geographical scale, such as that of agriculture and livestock farming. In summary, the goals of the Circular Bioeconomy (D'Amato et al., 2017; World Business Council for Sustainable Development, 2019) are shared by Agroecology: utilization of renewable resources, maximising the efficient use of resources and maximum possible reuse of waste, all of which leads to an improvement in the emissions balance by the agro-food system as a whole. The challenges in research in the Circular Bioeconomy referring to agriculture, livestock farming, forestry and food production, could be deemed to be included within the scope of the challenges facing Agroecology. Nevertheless, the fact that it appears explicitly in the denomination "Agroecology and Circular Bioeconomy" serves to highlight the importance of employing renewable and circular resources in the future of agriculture and food production.

In order to define and develop the principle challenges for the future in the fields of Agroecology and the Circular Bioeconomy, a panel of experts was created, comprising two coordinating researchers and twelve other investigators. The experts were selected in such a way that they all possessed a transversal vision close to that of Agroecology and the Circular Bioeconomy, from different areas of specialisation (within spheres such as Agronomy, Ecology, Food Sciences or the Social Sciences): soils, plant biodiversity, agroforestry systems, extensive livestock farming, composting and waste recycling, biogeography, archaeobiology, history, economy, anthropology and sociology. Eleven of the panel members were researchers from the CSIC and three were external. The latter were chosen to participate due to being renowned experts in Agroecology with vast experience in the transdisciplinary work inherent to this discipline.

Two rounds of consultation were extended in writing to the experts. In the first of these, they were requested to indicate the three main challenges they considered science was facing in the scope of Agroecology and the Circular Bioeconomy, with a brief justification of their choices. Having compiled and integrated all their answers, the coordinators drew up an initial report that grouped the proposed challenges in a rational manner into six main challenges, in turn subdivided into sub-challenges. This report constituted the basis for the second round of consultations, which entailed asking the experts to develop and specify further the sub-challenges indicated; additionally, they were also asked to provide information on the vision and the research resources of the CSIC concerning the different challenges and sub-challenges. Moreover, the coordinators contacted the specific experts on the panel on several occasions to develop or clarify specific aspects of the project. Lastly, the preliminary version of the project was reviewed by the experts.

2. IMPACT ON BASIC SCIENCE AND POTENTIAL APPLICATIONS

Basic science is conceived as fundamental research conducted without any immediate practical application; it is intended to bolster our knowledge of the fundamental principles of nature or of reality. On the contrary, Agroecology and the Circular Bioeconomy are considered to fall within the general scope of the applied sciences. Agroecology, due to its transdisciplinary nature, serves to articulate a relational structure between the Basic Sciences, such as Biology, Agronomy or Economy, among others, and therefore makes use of innovations from these disciplines. The co-production of scientific and peasant knowledge means that the conceptual development of Agroecology is based on results provided by an empirical reality. The comparative analysis of multiple empirical experiences becomes a necessary input with regard to formulating a theoretical analysis, because local agroecosystems and agro-food local systems respond to an environment with high multivariable diversity, a fact that implies different combinations of environmental, agrologic, agro-industrial, cultural or socioeconomic variables.

The challenges facing Agroecology and the Circular Bioeconomy proposed in the present chapter are in line with the scientific-technical, social and innovation objectives and priorities of CHALLENGE 2 of the Spanish Strategy for Science, Technology and Innovation 2013-2020, denominated *Food safety and quality, productive and sustainable agriculture, sustainability of natural resources, marine, maritime and inland waterway research*. This challenge highlights the particular relevance for Spain of aspects related to sustainable management and protection of agricultural, livestock farming and forestry resources, as well as the need to promote innovation and collaboration with small companies in the agro-food sector, in order to adopt a production model that is sustainable and efficient in relation to resources. The challenges put forward can also contribute to respond to some of the thematic priorities of CHALLENGE 5 *Climate Action and efficiency in the use of resources and raw materials*, which highlights climate change as one of the major threats to our society, and calls for efforts to strengthen our scientific knowledge of the causes and effects in Spain, due to the high climatic vulnerability of the country. Specifically, the challenges are in line with the goals of Challenge 5 that involve adaptation to climate change of agricultural and forestry systems, reduction of erosion and desertification risks, and conservation of biodiversity and natural heritage.

Within the European framework, the research challenges proposed will contribute to complying with the objectives and commitments identified in the

European Green Deal (*European Green Deal,* COM/2019/640 final), which constitutes the EU's major strategy for management and conservation of natural resources, aimed at rendering the EU climatically neutral by 2050. Specifically, this deal encompasses the Strategy for Biodiversity for 2030 (*Bring nature back into our lives*), which considers a Nature Recovery Plan whose objectives include a significant extension of agroecological objectives, an increase of the percentage of agricultural land managed under organic agriculture systems, and the promotion of local employment. Likewise, the Commission proposes that 10% of agricultural land be re-occupied by highly diverse landscapes, emphasising the need to reconcile agricultural production and biodiversity conservation, which is in accordance with the principles of Agroecology. The challenges addressed in the present chapter are also intended to help promote other major strategy included in the European Green Deal, called the *From farm to fork strategy*, aimed at creating healthy and sustainable food systems. The goals of this strategy include the development of an integrated plan of nutrient management intended to reduce the use of fertilisers and to promote the recycling of organic waste, as well as a plan of organic agriculture that stimulate both supply of and demand for organic products. All these aspects are considered in the following scientific challenges.

3. SCIENTIFIC CHALLENGES

3.1. Design of sustainable agroecosystems at landscape scale

In order to strengthen the sustainability of agroecosystems, on one hand there is a need to enhance the quality of its biophysical components, which have been transformed over time because of certain interrelations with the cultural and socioeconomic environment. On the other hand, however, agroecosystems must become capable of maintaining long-term biomass production without increasing external energy inputs, and this can only be achieved through a change in land management aimed at closing the main biogeochemical cycles at landscape scale. Research methodologies based upon participatory planning proposed from an agroecological perspective are essential to address the design at the landscape scale, and to make advances in the co-production of systems of indicators that allows comparing among highly diverse regions and local agro-food systems. Advances in this kind of methodologies would be very useful for the land management policies of local and regional administrations; an example of this involves the optimum location of nodes for last mile logistics.

3.1.1. Enhanced quality of fund elements of biophysical, socioeconomic and cultural nature

The flow-fund model is an analytical method of Ecological Economics devoted to study the process of production (Georgescu-Roegen, 1971). Funds are those elements that enter and leave the process, providing certain services over a given period, but they are never physically incorporated into the product (Vitucci Marzetti, 2010). Soil, biodiversity or the water cycle are biophysical fund elements of the agroecosystem.

Redesigning the uses of a territory's biomass under agroecological criteria means that the flows of energy, nutrients and water that sustain agricultural production must enable reproduction of biophysical fund elements. There is still a need for research based upon agroecological criteria on aspects such as correcting soil erosion, the risk of desertification or soil fertility. In this context, the application of methods of bio-intensification and of extensification can provide a wide range of versatile adaptive solutions. Furthermore, there is a need for more legume crops in our agroecosystems due to the role they play in providing nitrogen and restoring soil fertility.

Additionally, there is a need to improve the quality of the socioeconomic and cultural fund elements of the agroecosystem, as these are closely linked to the biophysical factors. Farmers and small and medium-sized agro-industries are usually price takers in the conventional globalized food system. Therefore, gaining control of the information flows of the food chain or being capable of deciding on food prices become crucial socioeconomic fund elements. Control of suitable genetic material for sowing, which involves exchanging and freely marketing traditional seeds, is an aspiration of producers in order to attain economic independence. A vital mission in Agroecology involves working on improving farmers' participation in research programs, since autochthonous varieties of crops and livestock races possess information flows that are adapted to local agro-environmental conditions.

3.1.2. Research on closing of biogeochemical cycles at landscape scale

Conventional intensive agriculture has simplified and degraded the quality of agricultural landscapes, a fact that has given rise to a loss of biodiversity and of biocultural heritage. There is a need to promote basic environmental services from within the agroecosystems, because functions such as conservation of genetic diversity, control of pests and diseases, or restoration of soil fertility are generally provided from outside the system. Optimum provision of these services requires, besides sustainable management of farms, a redesigning of agricultural landscapes, which calls for a balanced series of commitments and collective agreements by local societies.

Nonetheless, land design and management on a larger scale than that of farms require the application of an articulated body of empirical agroecological knowledge, which has just started to be generated in the last decades. To address this challenge, there is a need to consolidate and extend an agroecological proposal that is rooted in the Landscape Sciences, the geographical scope of which also includes agronomic, food, environmental, cultural, social and economic approaches. This objective, which is coherent with the commitment of the European Commission to the Circular Bioeconomy, corresponds to the third priority of the five strategies defined in the *European Strategy for Agricultural Research and Innovation:* this emphasises the need for "integrated ecological approaches from the farm to the landscape level".

3.2. Agroecology and Climate Action

Climate change implies an increase in temperatures, less rainfall, a higher frequency of extreme climatic events, and longer-lasting and more severe fires. All these factors will seriously affect the productivity of agriculture, forestry and livestock farming systems, which could cause a drastic change or even the disappearance of production and socioeconomic systems. Indeed, the Intergovernmental Panel on Climate Change (IPCC) has stated that Mediterranean ecosystems will become some of the world's most vulnerable systems in the coming years. A priority challenge therefore involves researching the role of Agroecology with regard to adaptation of Mediterranean agroecosystems to future climatic scenarios, as well as to their capacity to mitigate climate change.

3.2.1. Design of strategies for adaptation to future climate scenarios

It is a world priority to design farming strategies that involve less and more efficient use of water resources, in view of a hotter and drier future climate. To this end, there is a need to prioritise the use of crop species and varieties with a conservative water use strategy, giving a leading role to dry-farming crops and to livestock breeds that are adapted to the Mediterranean climate. Appropriate selection of species and varieties must be accompanied by a whole series of agroecological practices aimed at improving water storage in soils, such as slope correction using terraces, increase of soil organic matter, use of cover crops, or the establishment of agroforestry systems that take advantage of the benefits provided by trees (i.e. higher infiltration, less erosion, improved microclimate). There is a vital need to promote research into the adaptation of the different agroecological systems to lower water consumption.

3.2.2. Design of agroecological strategies for mitigating climate change

The agro-food system is one of the main sources of greenhouse gas (GHG) emissions. According to the last National Inventory of GHG emissions (Ministry of Ecological Transition 2020, data from 2018), the agriculture and livestock farming sectors alone represent 12% of total national emissions. In the European Union, agriculture and livestock farming are responsible for 10% of the GHG emissions (European Environment Agency, data from 2017), a percentage which at global level is 10.8 % (FAOSTAT, data from 2017). However, this figure only contemplates direct emissions from lands used for agriculture and livestock farming. If we also consider the emissions associated with transport and logistics of agricultural raw materials and food, the food industry, the transformation of forests to croplands, or with the energy used to produce agricultural inputs and machinery, we will see a sharp rise in the percentage of emissions corresponding to the agro-food system as a whole. Indeed, FAOSTAT estimates that by 2017 and at global level, if we include the emissions only from agriculture, livestock farming, forestry and certain other land uses (i.e. ploughing of forests), then the agro-food system represents 19.8% of the GHG emissions.

Agroecology aims to turn agriculture into a carbon sink to compensate for the emissions generated by the rest of the agro-food system, which in turn needs to be minimised (Altieri et al. 2005, Aguilera et al. 2020). Within this strategy, there is a need to investigate, promote and measure the agroecological practices that minimise emissions of GHG, which in turn entails maximising the capacity of agricultural soils to act as carbon sinks by means of, for instance, reusing organic waste or increasing biodiversity. Several international organizations are becoming increasingly interested in research on reserves and territorialised alternatives for carbon sequestration in agricultural soils: one of the initiatives with the clearest repercussions is the 4x1000 initiative, launched in the COP-21 by the French government and to which numerous countries have adhered, including Spain. This challenge is of a clearly political and economic nature, and it can be channelled by means of direct subsidies for agroecological practices promoting carbon sequestration without increasing emissions of N2O or CH4.

3.2.3. Interaction between climate change and other biotic stress factors: pests and diseases

Climate change can affect primary production not only in a direct manner by altering precipitation and temperature patterns, but also indirectly through its impacts on pests and diseases. A challenge involves evaluating the indirect consequences of climate change for primary production resulting from foreseeable losses associated with a higher incidence of pathogens. It is also a priority to base possible solutions upon a holistic approach, which goes beyond the conventional study of isolated interactions between host and pathogen, and which considers the health of the ecosystem as a whole. This approach should contemplate aspects such as conserving the diversity of trophic interactions, or the role played by the microbiome as a regulator and promoter of plant and animal health under stress conditions.

3.3. Circular Bioeconomy in agro-food systems

The concept of circularity proposes to make advances towards a state of "zero waste" for the entire agro-food system, through the re-circulation of water and the nutrients contained in the waste generated in the different phases of the food chain (manure and organic waste from agriculture, the agro-food industry, food distribution and consumption). Carbon, nitrogen, phosphorous, potassium or sulphur (CNPKS) constitute vital macronutrients that play a crucial role in plant nutrition and agricultural production. This re-circulation of nutrients is essential in order to substitute synthetic fertilisers. Some of these nutrients, like phosphorous, are extracted by non-renewable mining and others, like nitrogen, require a huge amount of energy to be obtained, thus causing numerous environmental problems such as aquifer pollution or N2O emissions. The broader challenge therefore involves identifying and disseminating the best techniques and practices for recycling bio-waste materials and recovering the respective nutrients, as well as investigating their corresponding socioeconomic implications and opportunities.

3.3.1. Making estimations of circularity at territorial scale

Any model of circular economy that is to persist in time on a planet with limited resources will have to address the behaviour of the CNPKS flows, and must ask how they are obtained and at what cost. In this sense, researchers propose to calculate the amounts of organic matter and nutrients entering and exiting a given geographic space, as in the case of large or small urban areas. Agro-food inputs account for a substantial proportion of the flows entering the metabolism of any territory. As for the flows exiting the territory, several main routes have been distinguished, such as bio-waste from agriculture, livestock farming and the food industry, excrements produced by the inhabitants and channelled through drainage systems to purifying plants, and the biomass from pruning and mowing in agricultural and public parks. The entry and exit flows of organic matter and nutrients can be estimated with the use of sociodemographic information at a municipal level. In this sense, the principal challenge involves in-depth research into the design of quantitative estimation models to calculate the entry and exit flows in a territory, using mechanisms for monitoring of real CNPKS flows. This will become essential to design local policies aimed at promoting circularity of materials and nutrients. This type of research would provide information on the advantages of different production options in a territory in terms of energy consumption or reduction of GHG emissions.

3.3.2. Establishing new uses for waste from agriculture, livestock farming and the food industry

It is highly necessary to investigate new uses for waste and sub-products from agriculture, livestock farming and the food industry, in order to diversify agro-food activities in a more economically and ecologically efficient manner, and to broaden the range of most commonplace uses (composting on the farm or the collection of organic matter for centralised compost production). We can highlight the following research lines: i) optimisation of the use of energy obtained from waste, such as anaerobic digestion, enzymatic hydrolysis or thermal treatments including pyrolysis or hydrothermal carbonisation; ii) production of fertilisers from organic waste by means of new bio-nanotechnological processes (those employing microorganisms, insects and annelids), extraction of phosphorous from wastewaters and ash, or the use of membranes for extracting nutrients from sludge and; iii) the use of organic waste for feeding invertebrate farms that produce protein for animal consumption. An evaluation of the eco-efficiency of all the former research lines must be made:

3.4. Agroecology and promotion of biodiversity

The strategies of intensification and specialisation in food production have caused a drastic reduction of specific and genetic biodiversity of agriculture, forestry and livestock farming. This is not only due to the generalised use of increasingly fewer agricultural or forestry varieties, or livestock breeds; it also results from the elimination of other species native to these agroecosystems that were considered to be competing with the species exploited for agricultural production. There exists scientific evidence that more diverse systems are more resilient to disturbances such as extreme climatic events, pests or diseases. The challenge here therefore involves restoring and conserving the general and cultivated biodiversity of agroecosystems.

3.4.1. Promotion of biodiversity of the past

Current environments are the result of a long evolution of former anthropic activity. Therefore, Archaeology and History are disciplines of particular interest with regard to addressing the processes of change and evolution of agricultural systems and landscapes, by observing our past through analysis of remains (whether biological, material or written). Archaeobiology enables us to explore, from a broad diachronic perspective, the different behaviours, motivations and decisions of human populations, which have brought human societies to resist or adapt to changing conditions, and even to survive drastic crises and impacts such as famines, pests or economic crises: The challenge consists of understanding how recovering the agriculture and livestock farming management systems that historically shaped the landscape, could help to reconcile primary production and biodiversity conservation. For instance, there is a vital need to prevent the loss of biodiversity associated with the traditional landscape mosaics, resulting from rural abandonment.

3.4.2. Promotion of biodiversity of the present

With regard to current biodiversity, our society must attempt to prevent the disappearance of our great diversity of agriculture, livestock farming and forestry. There is a need to go beyond the phase of conserving species in seed banks, thus cultivating and reproducing traditional crop and forest varieties and livestock breeds in experimental farms, and promoting their use. Crop diversification constitutes a fundamental challenge with regard to increasing crop resistance to pests and pathogens, as well as to droughts and extreme climatic events associated with climate change. These strategies were recommended at global level in the Nagoya Treaty (2014), complementary in themes of agriculture and livestock farming to the Convention on Biological Diversity, and by UE Regulation 2018-848 referring to materials of plant reproduction. Experimental research with pollination is starting to provide promising results for Agroecology.

3.5. Co-production and dissemination of agroecological knowledge

As has been stated, a particular feature of Agroecology is the co-production of knowledge by producers, consumers, scientists and the public administration. In the first place, it is of vital importance to continue to promote coordinated networks involving the different types of stakeholders in order to address specific, localised, changing and dynamic issues for the dissemination of agroecological knowledge. In Agroecology, scientific knowledge and praxis must not only be sequenced in one single direction, but rather bi-directionally.

Co-creation of hybrid knowledge by peasants and scientists is essential with regard to researching the mechanisms needed to promote biodiversity throughout history. A challenge facing Agroecology involves fully incorporating historical and cultural knowledge into research on local food production, cultivated biodiversity or local agroecosystems. Archaeobiology, Agricultural History, Ethnography or Anthropology do not only provide a diachronic view of the evolution of traditional practices and knowhow; they also provide information on the origin of the species, their uses, practices and appropriate technologies in different environmental and cultural scenarios.

Furthermore, given that climate change presents a whole range of uncertainties for farmers, thus diminishing their capacity for short-, medium- and long-term planning, another significant challenge refers to generating flows of information relating to agroecological practices and climate change, which, beyond the scientific scope, serves to send clear messages to the farmers.

Moreover, of particular interest for Agroecology is the challenge of promoting co-production of knowledge between producers and consumers. The consumers acquire information on the production logic of the agroecological approach, becoming empowered with the producers and with their personal situation. In turn, the producers acquire information on consumers' needs and desires, which enables them to adapt their supply to the demand.

Addressing this kind of challenge means that investigation should be accompanied by the implementation of public policies. In this sense, an important challenge involves promoting agreements on experimentation in agroecological cropping methods between the local or regional Administration and the farmers; the wide range of environmental conditions and typologies of crops, varieties, species and livestock breeds contrasts with the extremely low number of public or community facilities in Spain in this area. Another challenge lies in investigating, from the Social Sciences, how to enhance social recognition of the policies for conservation of agricultural biodiversity, which are often costly and quite unknown by citizens.

Additionally, a priority objective involves making the population aware of the concepts of Agroecology and the Circular Bioeconomy, local food identity, agricultural landscapes or short food chains, among many other themes. In many segments of society there exists quite a positive perception of the values inherent to Agroecology (ecological, local, etc.), but this has not yet materialised in a concrete demand for products from alternative production and marketing networks. The Cities' Strategies for Sustainable Food, issued by the 2015 Milan Urban Food Policy Pact, constitute a significant example of strategies for awareness, empowerment and participation of citizens in activities of sustainable food production, distribution, consumption and culture.

3.6. Agroecological local food systems and upscaling

3.6.1. Concept and design of agroecological local food systems

Many initiatives of social innovation do not provide the expected social benefits due to a lack of economies of scale and scope. A basic principle of Agroecology involves placing the idea of cooperation at the core of the analysis and the action, rather than competition, among the different stakeholders operating closely and belonging to the different phases of the food chain (farmers, food-processing industries, wholesalers, and retailers). Establishing synergies deriving from collective action among stakeholders who are territorially close and who possess an agroecological vocation, constitutes the principal solution to the isolation and fragmentation habitually occurring in many innovative experiences.

This poses the theoretical and empirical challenge of developing a new concept of "agroecological local food systems" (ALFS): a diffused and specialised local network of farms, food-processing industries and other agroecologically-oriented companies. The following elements should be jointly considered by stakeholders as criteria to be optimised: the territorial factors associated with the territorial specificity and local identity of the food products, and the agroecological principles such as closure of biogeochemical cycles, promotion of biodiversity, enhancement of the biophysical capital, or marketing based upon short food chains.

An aim of the ALFS is to supply healthy local food products; these should be accessible to the population, in terms of price and purchase location, and should be sustainably grown, with fair prices paid to the farmers. The ALFS also aim to recover cultural uses linked to diet as a way of actively preserving a territory's cultural heritage. There exist a consolidated body of literature on local food systems that combine territorial approaches with supply-chain analysis (Sanz-Cañada, 2016), but there have been no proposals defining or propagating criteria for the agroecological orientation of these systems. The task of systematising, defining and classifying experiences of ALFS constitutes a huge conceptual and methodological challenge that will probably be very helpful in the design of public policies and civil society actions.

3.6.2 Agroecological food hubs: collective action, governance and upscaling

There have been numerous experiences in alternative production and consumption, presenting an unequivocal agroecological orientation, in recent years in Spain. These alternative networks, however, frequently linked to social movements, have often been relatively short-lived or have shown insufficient growth, failing to involve the population on a broader scale. In this sense, the challenge facing Agroecology is to scale-up, broadening the scale of both production and consumption. If this change of scale is led by the collective action of small producers, not only economies of scale can be generated in farming and in food processing in the medium term, but significant logistic and distribution synergies as well. Nonetheless, the most serious obstacles for achieving the upscaling come from the logistics and physical distribution of food, which currently respond to a fragmented model of storage, picking or transport, at high costs and with a big carbon footprint. Strategies aimed at optimising transport must not only affect flows of food from the farm to the table; inversely, they should involve flows of domestic bio-waste to agro-composting plants.

In this context, one of the biggest challenges, in relation both to research and to policies, involves the creation of food hubs, or associative centres of small producers, processors and retailers of local and organic food. The food hubs aim not only to set up centres for optimal storage and exchange of products, but also to cooperatively integrate a whole range of functions aimed at reducing costs and the carbon footprint or increasing customer portfolios, such as the following ones: transport sharing; joint promotion and marketing; joint planning of production in the case of fruit and vegetables farmers; or the collective organisation of inverse logistics of bio-waste. As these experiences are innovative, it would be advisable to investigate, for instance, aspects such as forms of organisation, governance systems, strategies aimed at reducing the carbon footprint, or collective involvement in marketing functions. The models of organisation, logistics and distribution must be flexible and scalable, in order to be adaptable to demands like the public purchase of hospitals, schools or universities.

CHAPTER 2 REFERENCES

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SUMMARY FOR EXPERTS

6A. CHALLENGES IN AGROECOLOGY AND CIRCULAR BIOECONOMY

Agroecology: a transdisciplinary scientific approach that attempts to investigate in a holistic manner the interrelations existing among the agronomic, biophysical, ecological, social, cultural, economic and political components of agroecosystems. It is intended to serve as a connection among the basic sciences to address issues of agro-food sustainability

1. Design of sustainable agroecosystems at landscape scale	• *1.1. Enhanced quality of fund elements of biophysical, socioeconomic and cultural nature* • *1.2 Research on closing of biogeochemical cycles at landscape scale*
2. Agroecology and Climate Action	• *2.1 Design of strategies for adaptation to future climatic scenarios* • *2.2. Design of agroecological strategies intended to mitigating climate change* • *2.3 Interaction between climate change and other biotic stress factors: pests and diseases*
3. Circular Bioeconomy in agro-food systems	• *3.1 Making estimations of circularity at territorial scale* • *3.2 Establishing new uses for waste from agriculture, livestock farming and the food industry*
4. Agroecology and promotion of biodiversity	• *4.1 Promotion of biodiversity of the past* • *4.2 Promotion of biodiversity of the present*
5. Co-production and dissemination of agroecological knowledge	•*Co-production of knowledge: i) scientific and peasant; ii) incorporating historical and cultural knowledge; iii) between producers and consumers* •*Promoting networks of local stakeholders for disseminating knowledge* •*Promoting agreements on experimentation in agroecological cropping methods* •*Enhancing social recognition of the policies for conservation of agricultural biodiversity*
6. Agroecological local food systems and upscaling	• *6.1 Concept and design of agroecological local food systems* • *6.2 Agroecological food hubs: collective action, governance and upscaling*

SUMMARY FOR THE GENERAL PUBLIC

6A. CHALLENGES IN AGROECOLOGY AND CIRCULAR BIOECONOMY

What is Agroecology?

Transdisciplinary research approach to interrelations among the agronomic, biophysical, ecological, social, cultural, economic and political components of agroecosystems

What are the challenges?

Agroecology to cool the planet: Climate Action

Bio-waste reuse and recycling: Circular Bioeconomy

Promoting biodiversity

Co-production of hybrid knowledge among scientists and farmers

Upscaling of production and consumption for better and cheaper distribution

Promotion of sustainable landscapes

How do we achieve them?

Promoting biodiversity of the present and the past

Increasing biological interactions and synergies among the plant, animal and microbial components of the agroecosystem

Reducing the use of external energy inputs for agriculture and livestock farming

Closing biogeochemical cycles

Promoting mutual knowledge and relationships between producers and consumers

Marketing on commercially and geographically short chains

Promoting local networks for disseminating knowledge

Promoting synergies derived from local-scale cooperation among farmers, agro-industries, cooperatives, consumers and local institutions involved in agroecology

CHAPTER 3

ABSTRACT

Animal production, both terrestrial and aquatic, is an economic, social and environmental key sector. Its main objective is to provide affordable, safe and quality food for human consumption, while guaranteeing the sustainability of production processes and the conservation of the ecosystems that support them.

KEYWORDS

animal health and welfare
animal production
aquaculture
environmental impact
fishing
livestock
quality of animal products
resilience
sustainability

CHAPTER 3

COMPREHENSIVE IMPROVEMENT OF LIVESTOCK AND AQUATIC SYSTEMS

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EXECUTIVE SUMMARY

Terrestrial and aquatic animal production are key sectors in Spain from the socioeconomic point of view, not only for the value of production but also for the employment it generates, both direct and indirect (agricultural activity for the production of animal feed, boats, machinery, feed mills, the veterinary pharmaceutical industry, etc.). This activity is also important from the environmental point of view and supports a powerful agri-food industry, which has an important international projection and contributes significantly to the trade balance. Any type of production system currently faces major challenges: 1) Increasing the efficiency in the production of nutritious, healthy and safe food for human consumption; 2) Ensuring animal health and welfare; 3) Reducing the environmental impact of animal production; 4) Improving the quality and traceability of animal products; 5) Adapting the production systems to the available resources and new goals and increase their resilience against the global social, economic and environmental changes. Research aimed at solving these challenges faced by animal production will generate knowledge about basic aspects of a biological and technological nature and establish scientific-technical bases for the development of future animal production systems. At the CSIC there are research groups that work in different disciplines such as Animal Nutrition, Livestock Systems and Land Use, Animal Health, Genetics, Epigenetics and Genomics, Parasitology and Immunology, Reproduction, Conservation and Transformation of Fishery Products,

Food Safety, Human Health, Ecology, Aquaculture, Biodiversity, Ecosystem Loading Capacity and Governance Systems in Environmental Management. This allows inter and multidisciplinary approaches of enormous potential and interest, and provides opportunities for collaboration not only between groups that address these various disciplines, but also with groups from other areas such as Food Science and Technology, Biomedicine, Biotechnology, Environmental Physics and Ecology or Social Sciences. Facing the challenges of Animal Production requires, among other things, the provision of equipment and infrastructure, large animal and research facilities and human resources.

1. INTRODUCTION AND GENERAL DESCRIPTION

1.1. Social, economic and strategic importance of animal production

Terrestrial and aquatic animal productions are key sectors in Spain from the socioeconomic point of view. This production, not only represents 1.2% of GDP) but also generates more than 400,000 direct jobs and many more indirect jobs in agricultural activities for the production of animal feed, ships, machinery, feed mills, veterinary pharmaceutical industry, etc. This activity is also important for the environment and it supports a powerful agri-food industry (6% of GDP and 8% of employment), which has a significant international projection (9% of exports from the entire EU) and a positive contribution to the trade balance of around 11 billion euros.

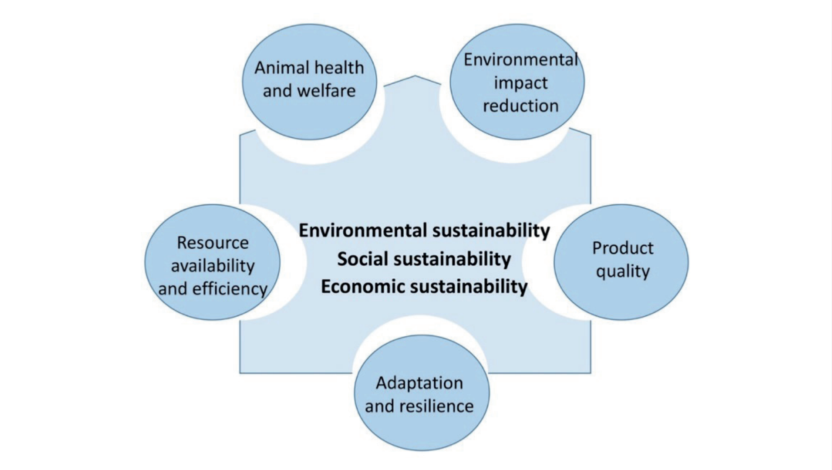
The food production of animal origin is essential for food security and sovereignty (Norman et al., 2019) and livestock activity, associated with some production systems, is also essential for the maintenance of the population in rural areas and the conservation of natural heritage. Since 2000 the rural population in Spain has decreased by almost 1 million people (MAPA, 2019). On the other hand, Spain is one of the EU countries that depends most on fishing, with numerous coastal areas where fishing of fish and shellfish, often artisanal or small-scale, has enormous social, economic and cultural importance. Additionally, Spain is the country with the highest fishing capacity, number of jobs, processing capacity and export/import in the EU. Furthermore, Spain is one of the EU countries with a high production capacity for aquaculture products.

1.2. Current and future challenges of animal production

The main challenge for animal production, both aquatic and terrestrial, is to provide enough food, affordable and with proven quality and safety, for a constantly growing world population, which is estimated to be close to 10 billion people by 2050. Addressing this challenge through sustainable animal production, capable of maintaining ecological processes that guarantee the conservation of ecosystems, require the coordinated consideration of three dimensions: environmental, social and economic. However, the challenges in these three dimensions vary depending on whether the control of the production system is direct or indirect. Direct control is exercised within the framework of agricultural exploitation (e.g., livestock and aquaculture of fish and many mollusks), over the reproductive rate and all - or practically all - of the life cycle of the organism that is cultivated. Indirect control is exercised over the capture or extraction without managing the reproduction of the organisms, which totally depends on the ecosystem in which the exploitation is carried out (hunting, fishing of fish and shellfish. and mussel aquaculture). In these activities the influence of the environment on production is absolute and the greatest challenges are based on knowledge of the functioning of the ecosystem, its productivity and resilience. Another notable difference is that in hunting, fishing and shellfishing, under indirect control, the resources exploited are public and it corresponds to the public administration to develop the most appropriate mechanisms for managing the activity.

Any of the production systems currently face five major challenges: 1) Increasing the efficiency in the production of nutritious, healthy and safe food for human consumption; 2) Ensuring animal health and welfare; 3) Reducing the environmental impact of animal production; 4) Improving the quality and traceability of animal products; 5) Adapting the production systems to the available resources and new goals and increase their resilience against the global social, economic and environmental changes (Figure 1).

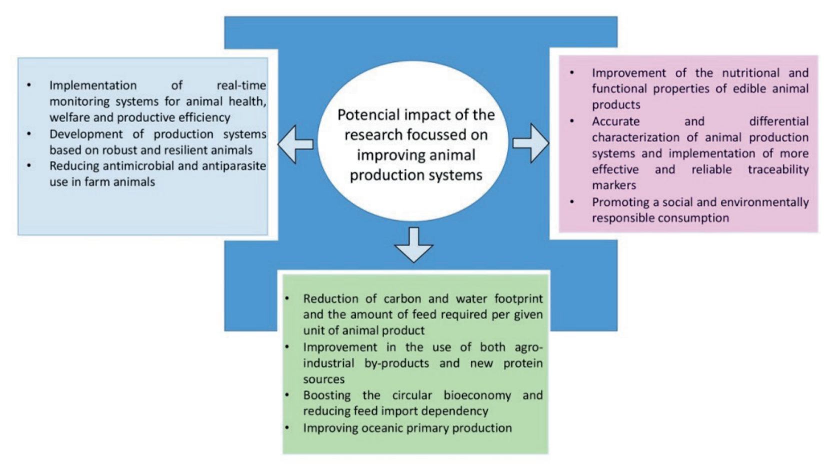
FIGURE 1. Diagram of the factors that influence sustainable production.



2. IMPACT ON BASIC SCIENCE AND POTENTIAL APPLICATIONS

Research aimed at solving the challenges faced by animal production will generate knowledge on basic aspects of biological nature and technology, applicable to other areas of knowledge, and establish scientific and technical bases for the development of future animal production systems. The impacts that derive in basic science and their potential applications for the productive sector are summarized in Figure 2.

FIGURE 2. Impacts of research oriented at the comprehensive improvement of terrestrial and aquatic animal production systems.



2.1. Impact on basic science

- Development of simulation models and methods that reduce the dependence on experimental animals and improve animal welfare.
- Design of new scientific approaches to the study of innovative parameters in animal production, such as resilience.
- Progress in the knowledge of the epidemiology and pathogenesis of diseases as well as the mechanisms involved in the development of antimicrobial and antiparasitic resistance.
- Development of new scientific strategies for obtaining effective vaccines.

- Greater knowledge of the interrelationships between the diet, the microbiome and the immune system of animals, as well as the biological bases (genetic, epigenetic and molecular) that determine efficiency and resilience.
- Implementation of technologies (sensors, software, big data) for the continuous collection of data, which allow assessing animal health and well-being, the efficiency of the production system and the management of exploited natural resources, particularly fishing.
- Development of cleaner and more efficient energy technologies in the field of shipbuilding and more selective fishing technologies.
- Generation of more sustainable aquaculture facilities with less environmental impact.
- Development of new models that allow a better understanding of the marine ecosystems functioning and the integrated management not only of fisheries, but also of all ecosystem services.
- Improvement of international governance processes considering the environmental, social and economic aspects.

2.2. Potential applications

- Development of new production systems based on the exploitation of more robust and resilient animals, reducing the use of antimicrobials and antiparasitics.
- Conservation and characterization of genetic resources and increase in the diversity of systems, improving their adaptation to local resources and the productive objective.
- Implementation of epidemiological models in animals, wild and domesticated, and their relationship with humans.
- Implementation of continuous monitoring systems for animal health, welfare and productive efficiency.
- Reduction of the carbon and water footprint and the amount of nutritional resources required by the animal (use of agro-industrial by-products, new sources of protein), reducing competition with humans.
- Implementation of new tools for environmental observations and management.
- Boost of the circular bioeconomy and local commerce, reducing the import and transport of animal food.
- Improvement of the nutritional value and healthy properties of animal

products, promoting socially and environmentally responsible consumption, based on better consumer knowledge of different animal production systems characteristics.
- Accurate and differential characterization of production systems and implementation of efficient and reliable traceability markers.
- Development of clean and energy efficient technologies in the field of shipbuilding and more selective fishing, and improvement of oceanic primary production, which represents the first link in the food chain.
- Improvement of the management of abandoned lands, favoring their conservation (reduction of accumulated plant biomass) and increasing carbon sequestration.
- Promotion of new systems of governance that reduce political, social, economic, environmental and health conflicts.

3. KEY CHALLENGES

3.1. Increasing the efficiency in the production of nutritious, healthy and safe food for human consumption

The increase in animal production implies a greater demand for land, water and nutrient resources, increasing competition with humans and other animal species with different digestive physiology and efficiency (ruminants vs. birds vs. fish). The use of plant resources and agro-industrial by-products for other purposes, such as obtaining energy or biorefinery products, also contributes to intensifying this competition. In Spain, in addition, agricultural yield will be reduced by 25% due to the decrease in rainfall derived from climate change, which will reduce the availability of food (Medina-Martin, 2016). Pollution also has a negative effect on the availability of resources, especially water. In the marine sphere, the development of new activities such as mining, or the generation of energy compete for the use of the territory with animal production. In this context, it is necessary to prioritize research aimed at reducing competition for resources with human beings and developing comprehensive mechanisms for the management of the territory, uses and governance, which allow increasing the efficiency of the use of available resources and, inconsequence, the efficiency of animal production.

Fishing and aquaculture are less efficient processes, in ecological terms, than livestock farming, since they act on species with higher trophic levels (Scientific Advise Mechanism, SAM, 2017). In particular, European fish farming is based on species with a very high trophic level such as Atlantic salmon (*Salmo salar*), trout (*Oncorhynchus mykiss*), sea bream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*) (Tacon et al., 2010), which affects species of lower trophic levels, usually captured in other latitudes and that provide raw materials for the elaboration of feed used in fish farming. To mitigate this effect, progress has been made in substituting fishmeal and fish oils with others of plant origin in aquaculture feed (Sutili et al., 2018). On the other hand, European and Spanish aquaculture in particular, considered globally, offset to some extent the impact due to the large production of bivalve mollusks, which are basically herbivores. Aquaculture may have extraordinary relevance for the food supply in the future, as 90% of the ocean remains to be exploited for this type of production, which is currently only carried out in continental and coastal waters. On the other hand, the geographical situation of Spain guarantees access to Atlantic and Mediterranean waters, with very different conditions, allowing diversification of aquaculture production. However, like agriculture and livestock, fishing and aquaculture present complex problems that limit their development (Scientific Advise Mechanism, SAM, 2017). The high cost of maintaining facilities away from the coast (including its impact on the carbon footprint, loss of production due to waves, etc.) greatly reduces its efficiency, which is why it is necessary to develop better, more resistant and low-tech cost management procedures. In the case of fishing of fish and shellfish, the availability of resources is not guaranteed, since there is no control over production and, exploitation is limited to capturing or extracting surpluses that the ecosystem itself is capable of producing. In addition, fishing exploits the ecosystem as a whole since the captures are usually multispecific, which generates discards and ecosystem overexploitation. Finally, the efficiency of the fishing activity depends on the cost of the catch, since there is no cost in production. However, the catch is made in a very energy inefficient medium, such as a fishing vessel, especially in areas far from the coast. Trying to alleviate costs also produces a higher volume of discards, overexploitation and reduced product quality. There are two main challenges to improve fishing efficiency: on the one hand, adjusting catches to the level of production of ecosystems and exploited species, an eminently ecological problem; on the other hand, the need for a great technological development in two essential aspects such as improving the selectivity of fishing activity and reducing energy costs, by using cleaner and cheaper energy and reducing spending with better fishing gear, more efficient engines and better logistics and management previous to go to the sea.

Challenges to address (Figure 3):

3.1.1. Develop effective systems in the direct use of terrestrial and aquatic natural resources, promoting the reorientation of fishing and aquaculture towards species with a lower trophic level. In the terrestrial field, design and evaluation of mosaic-type systems, with potential use by livestock of a significant area of the territory (pastures), which could reduce the risk of fires due to the uncontrolled increase in plant biomass.

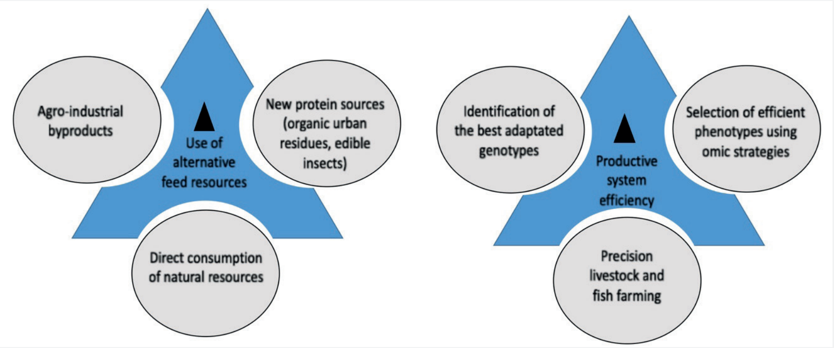
3.1.2. Increase and adapt the use of alternative or unconventional resources to feed animals, which does not imply competition with human food, such as agro-industrial by-products, fish discards, algae, insect proteins, etc.

3.1.3. Develop strategies to increase production efficiency: selection of more efficient individuals using omics techniques; identification of the factors that regulate long-term efficiency and of the physiological and molecular mechanisms involved, and exploring the potential of epigenetics and genetic editing to generate phenotypes/genotypes more efficient and adapted to the environmental conditions of production areas.

3.1.4. Implement precision animal production through the development of technologies for continuous monitoring of productive and reproductive parameters, individual and remote control of animals, and automated control of facilities and robotization of routine and mechanical processes.

3.1.5. Reutilization and valorization of fishery waste for its transformation into high quality, safe and nutritive products that meet the demands of society, incorporating innovative technologies and well-defined value chains.

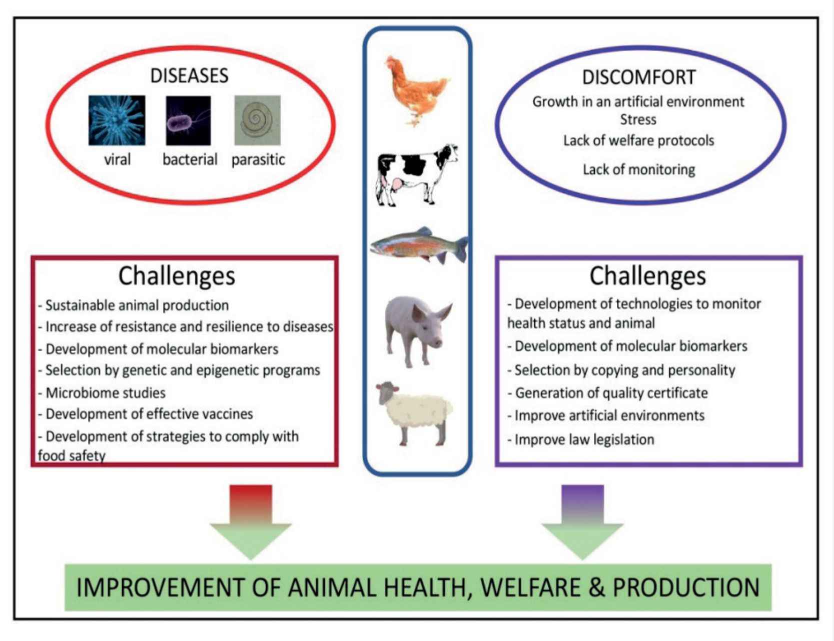
FIGURE 3. Diagram of the use of alternative resources and efficiency of the production system.



3.2. Ensuring animal health and welfare

Ensuring animal health is the basic pillar of any production system, not only for ethical, but also economic and public health considerations. Figure 4 summarizes the main challenges associated with animal health and welfare. Sick animals can transmit diseases directly or indirectly to the human population and their production is less efficient and more expensive. The intensification of production systems, derived from the increased demand for food of animal origin, the increasing movement of animals and goods between countries and the changes due to climate change have increased the pressure on animal health. All this together with the lack of vaccines and the insufficient response to genetic selection programs to stimulate animal resistance to certain diseases, has increased the use of drugs contributing to the development of antimicrobial and antiparasitic resistance (Defoirdt et al., 2011; APROMAR, 2016; Watts et al., 2017). These resistances represent a major public health problem, and if the situation is not reversed in 2050 more people could die from this cause than from cancer (World Health Organization (WHO), 2015). In this context, the primary objective is to develop strategies for the prevention and control of diseases, through the implementation of biosafety measures, the development of effective vaccines and the increase in the robustness of animals. This requires a greater understanding of diet-microbiome-immune system interaction and of the mechanisms of resistance development. Evaluating biological and chemical therapeutic combinations is essential to establish effective therapies. Animal health and well-being are interdependent processes, and the lack of well-being can make animals more vulnerable to infectious diseases. Although standardized procedures have been established to assess animal welfare in some species, it is necessary to extend them to other species and levels of the production chain (farm, transport, capture or slaughter), and to identify objective and accurate markers using Information Technology and Communication (ICTs), biosensors and Bigdata, which will allow continuous monitoring of animals (Neethirajan et al., 2017; Martos-Sitcha et al., 2019). In the case of hunting, fishing or shellfishing, animal health and well-being are not under the direct control of the exploitation but depend on the health of the ecosystem.

FIGURE 4. Outline of the ensuring animal health and welfare challenge.



Challenges to address:

3.2.1. To increase the robustness (resistance) and resilience (tolerance) of animals to diseases through genetic selection strategies and "omic" technologies (genomics, metagenomics, epigenetics, transcriptomics, proteomics, interactomics and metabolomics), for example, generation of a phenotype favorable for broodstock animals. Further, the role of the microbiome in animal health in general and, particularly, in young animals is of especial interest.

3.2.2. To develop strategies to improve food security and control of zoonotic diseases: disease risk-based surveillance (epidemiology), early detection, preventive measures such as vaccines and probiotics, and alternative strategies such as biosecurity (including reproductive technology and the effectiveness of drug and vaccine delivery systems), vaccines applying quantum vaccinology technologies, Big Data and Machine Learning for the identification of antigens and protective epitopes (the immunological quantum), control of toxins and contaminants and the study of their effects on animals and humans, application of model animals with a short life cycle and with available resources.

3.2.3. To develop new therapeutic strategies, based on a better understanding of the mechanisms involved in the development of resistance and on the identification of new antimicrobial molecules and phage therapies.

3.2.4. To improve animal welfare through the implementation of surveillance systems that continuously monitors animals. This will involve advancing in the study of stress physiology, identifying reliable biomarkers of welfare, developing biosensors and protocols for the identification of animal behaviors and personalities, or the use of technologies based on remote control and tools such as those provided by the Copernicus program of the EU. Research for the improvement of animal welfare must extend to the different stages of the production system, including the transport and slaughter of animals.

3.2.5. To develop highly technical facilities (geolocation, electronic fences, biosensors, drone surveillance) for improving the management of production systems.

3.2.6. To stablish legislative regulation and new protocols to improve animal welfare and reviewing slaughter methods, especially in aquaculture production.

3.3. Reducing the environmental impact of animal production

Animal production has an undoubted environmental impact, which must be reduced. Reciprocally, environmental degradation impacts animal production, generating important challenges, such as those related to the carbon footprint and pollutants and the loss of habitats and ecosystems, which cause a reduction in biodiversity. Greenhouse gases (GHG) represent one of the main pollutant emissions from animal production systems. In 2018, Spanish livestock generated 8.9% of total GHG emissions and 61.3% of total anthropogenic methane emissions (MAPA, 2020). Of the total methane emitted, 72.2% was produced in enteric fermentation, with ruminants being the main contributors (95.2%) and the rest generated in manure management, with pigs being the majority contributor (75.8 %). Fishing and aquaculture also contribute to global CO_2 emissions; fishing vessels emitted 207 million tons of CO_2 in 2016 (Geer et al., 2019). The impact that aquaculture has on climate change is not well understood, but the parallelism with the effects of terrestrial animal production seems obvious (FOESA, 2013). In fact, it has been estimated that aquaculture produced around 390 million tons of CO_2 equivalents per year which represents about 7% that of agriculture. However, the carbon footprint has a very uneven impact on the different cultivated species. For example, bivalve culture has a negative net footprint due to carbon fixation in the shell. The research carried out has allowed us to establish the relative importance of the different sources of GHG and to design strategies for their reduction related to food, manure management or other sources. Early manipulation of the microbiome and the use of additives, by-products, plant extracts, etc. can modulate ruminal fermentation decreasing methane emissions. In the case of fisheries, emissions could be reduced 10-30% through the use of efficient motors, larger propellers, the improvement of the shapes of the vessels or, simply, reducing their average speed. The development of more effective procedures for the genetic improvement of animals and the use of new methods of modifying enteric fermentation (phages and bacteriocins) or of better management of the generated residues could also contribute to this reduction. The reduction of the environmental impact of livestock farming, however, cannot focus exclusively on mitigating GHG emissions, but soil and water contamination must also be considered, evaluating the life cycle of the entire chain of production. In addition to its contribution to climate change, livestock, fisheries and aquaculture have a direct impact on ecosystems, through: 1) the destruction of habitats to obtain pastures, the effect of fishing and the occupation of the territory by marine facilities; 2) the alteration of biological communities due to excessive hunting, overfishing, depositions and food residues, including fish discards; and 3) the introduction of exotic and invasive species that also may act as vectors for new diseases. This leads to an important loss of biodiversity, alteration of the food chains and elimination of essential ecosystems. In the terrestrial ecosystem this impact has been occurring for centuries, so the main challenge is to recover ecosystems in a manner compatible with livestock activity. In the marine environment, the impact is much more recent and, therefore, less, making it necessary to achieve an aquaculture farm that respects the ecosystem. In recent decades, marine ecosystems have been notably degraded due to climate change, pollution, coastal habitat overexploitation, and the lack of integrated ecosystem management and governance, problems that significantly affect animal production in the marine environment and which are analyzed in depth in Strategic Theme 13 (Oceans).

Challenges to address:

3.3.1. Comparative study of the environmental balance (life cycle analysis) of current production systems and the impact of strategies aimed at reducing emissions of GHG and other pollutants through simulation models.

3.3.2. Improve methodologies that allow quantifying GHG emissions from animals and the wastes generated (manure, slurry) and identifying the biological bases (genetic, epigenetic, microbiological, biochemical) responsible for the individual variation in GHG emissions and others pollutants.

3.3.3. Improve the management of wastes and develop comprehensive solutions, collective management and product valorization.

3.3.4. Develop sustainable aquaculture techniques such as semi-intensive culture systems for filter species (bivalve mollusks), polyculture of fish with bivalves and integrated multitrophic culture (algae-herbivores-fish) that reduce the environmental impact of aquaculture.

3.3.5. Developing cleaner fuels and more efficient engines on fishing vessels

3.3.6. Develop specific detection technologies for fishery resources, which improve selectivity and efficiency in the catch, as well as more selective and less harmful fishing gear for the seabed, accompanied by improved mapping of the seabed for the detection of vulnerable and / or rich areas of biodiversity.

3.4. Improving the quality and traceability of animal products

The quality of animal products is closely related to consumer demand and preferences and of market characteristics as well. This has given rise to different criteria for evaluating the quality of the products (Figure 5). A first criterion is the safety, both of the treatment and conservation of the product (hygienic-sanitary conditions) and of the product itself, which can be a transmitter of pathogens or toxic substances. This poses well differentiated challenges, involving research related to food preservation and, in particular, related to microbiological research. Lack of proper prevention can promote the transmission of infectious diseases. A second criterion is the acceptability of animal products, determined by factors such as price or sensory properties, which are key in consumers' decision. Composition is another increasingly relevant criterion, especially with regard to the content and type of fat and the presence of oxidized compounds with atherogenic and carcinogenic potential. The consideration of processed and red meat as carcinogenic and probably carcinogenic, respectively, reduced their consumption, while consumption of fish and shellfish soared in the EU, putting significant pressure on fishing and aquaculture. Achieving the sustainable exploitation of marine products is a matter of Strategic Theme 13 (Oceans), but it continues to be a challenge to increase the quality and shelf life of fishery and aquaculture products by improving technological processing and conservation.

The identity of the product, taking into account defined by geographical origin, animal species or production system are becoming increasingly important. The production system, associated with its degree of animal welfare and environmental impact, increasingly worries consumers. The increase in the consumption of marine products has also increased the import of fish and shellfish. The strict control of traceability and labeling as well as the certification of origin and the sustainability of the final product, are current and future challenges that our society demands.

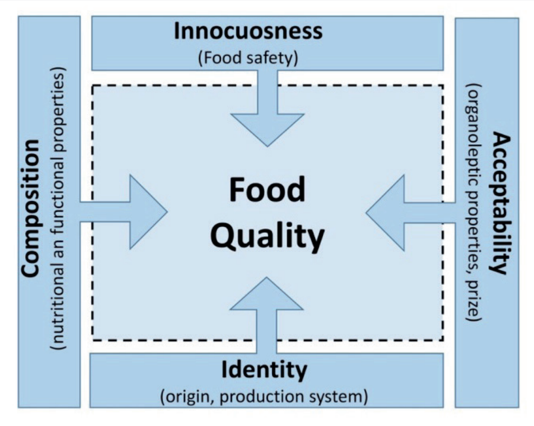


FIGURE 5. Factors necessary to guarantee the quality of the food products produced.

Although for decades the priority objectives of research have been related to increase animal production and cost reduction, current research focuses on the effects of the consumption of certain animal products on health, enhancing their functional properties (antioxidants, healthy profile of fatty acids, anticancer properties) and eliminating natural compounds harmful to health (such as derivatives free of b-casomorphine-7 in milk). However, this research should be approached in the future with a holistic approach, addressing the interrelation efficiency and environmental impact, and clearly establishing the differences between production systems. The improvement of the identity of the product must be accompanied by scientifically validated procedures that can certify its sustainable production conditions.

Challenges to address:

3.4.1. Reduce contaminants and increase the shelf life of animal products for human consumption, through strategies implemented in the production phase (use of natural feed additives to improve the shelf life of products and reduce the use of synthetic preservatives), and the development of analytical methods for the rapid evaluation of contaminants in food and water.

3.4.2. Develop strategies for the elimination of the microbial load in products of animal origin, and the control of fish parasites and allergenic proteins.

3.4.3. Develop application technologies on board fishing vessels that improve the quantification/characterization, conservation and processing on board and the quality of fishery products.

3.4.4. Increase the added and differential value of animal products and improve their nutritional and healthy properties.

3.4.5. Develop analytical techniques (NIRS, genomic techniques, etc.) that allow the implementation of new traceability markers in animal products to identify the diet, breed and origin of the animals. In the case of aquaculture, it would also allow the identification of fish escapes that are caught as wild.

3.4.6. Study non-nutritional applications of food and by-products of animal origin and identification of bioactive compounds.

3.4.7. Improve consumer knowledge of animal products.

3.5. Adapting the production systems to the available resources and new goals and increase their resilience against the global social, economic and environmental changes

The economic, social and environmental pressure currently forces us to reconsider animal production systems, so that they adjust to the availability of local resources and environmental conditions. It will be necessary to make projections of how climate change will influence the environmental conditions of production areas and evaluate the adaptation of current systems to these new conditions. For some species, there is abundant scientific information that will need to be reanalyzed, probably with modern computerized search procedures (algorithms), to evaluate, a priori, the ability to adapt, but also to establish potential strategies that allow this adaptation (change of target species, breed, productive orientation, etc.). For many other species, the information is scarce and it will be necessary to evaluate their physiological adaptation capacity and the management procedures that favor this adaptation. Species caught or collected in the natural environment are extremely vulnerable to climate change, which acts synergistically with exploitation, eroding the resilience of the ecosystem. The resilience of systems is a key challenge, as we move towards scenarios that are not very stable over time due to changes in socioeconomic and environmental conditions. Production systems must be able to adapt to these temporary fluctuations, that is, be resilient. Resilience is a complex phenomenon that involves plants, animals and the food production chain for humanity. Research in this area, related to animal production is very recent and it will be necessary to establish evaluation criteria and identify the biological bases that determine the variability in the resilience of animals and ecosystems. The development of resilient systems is a transversal objective, which must take into account the interaction with animal health and welfare, the efficiency, the environmental impact and the quality of the products obtained, but also the resilience of the socio-economic system, which depends on the type of animal production system.

Challenges to address:

3.5.1. Evaluate the effect of the modification of environmental conditions caused by the climate crisis on production systems.

3.5.2. Design and evaluate management systems or strategies more appropriate to new environmental conditions, by identifying species and breeds better adapted to environmental conditions and production objectives, and adapting management conditions to mitigate the potential effects of climate change.

3.5.3. Develop a scientific methodology to assess individual and overall resilience of the production system, by identifying the biological bases that determine individual resilience and establishing strategies to improve this capacity in production animals.

3.5.4. Comprehensively assess the resilience of production systems to changes in socioeconomic conditions.

3.5.5. Improve governance mechanisms in production systems that incorporate better management of land use, promoting circular economy practices, and that incorporate the socio-economic value of livestock, aquaculture and fishing farms.

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ANNEX 1

Annex 1. Relationship to the priority odjectives of the other organizations:

- The challenges to be faced in the future by improving the integral production of livestock and aquaculture systems are closely related to the priority objectives of other National and International Organizations, including the following:

Challenges of the Society of the State R&D Plan 2017-2020

- Challenge 1. Health, Demographic Change and Well-being
- Challenge 2. Bioeconomy: Sustainability of Primary and Forest Production Systems,
- Food Safety and Quality, Marine and Maritime Research and Bioproducts
- Challenge 5. Climate Change and Use of Natural Resources and Raw Materials
- Challenge 7. Digital Economy, Society and Culture

Global challenges and competitiveness of the Horizon Europe 2021-2027

- The second pillar supports research that addresses societal challenges and industrial technologies in areas such as digital technologies, energy, mobility, food and natural resources.

FAO Sustainable Development Goals (SDGs), 2030 agenda

- SDG2. Zero hunger
- SDG3. Health and welfare guarantee a healthy life and promote well-being for all at all ages
- SDG6. Clean water and sanitation
- SDG12. Responsible production and consumption
- SDG13. Climate action
- SDG14. Submarine life
- SDG15. Terrestrial ecosystem life

Global Agenda for Sustainable Livestock (FAO)

- Increase efficiency
- Protect resources
- Increase resilience
- Improve producers' livelihoods and human well-being
- Improvement of political management

The Animal Task Force, for a sustainable and competitive livestock sector in Europe

- Towards a climate smart European livestock farming
- Balance Production/Consumption: Animal farming for Humans 'well-being and planetary health
- Livestock, the key in a circular bioeconomy
- Precision Livestock Farming
- Putting the i in livestock: innovation for productive and sustainable livestock farming
- Resource-use efficiency
- Practical actions towards low-carbon livestock, FAO
- Boost the efficiency of animal production and the use of resources
- Intensify recycling and reduce losses through the circular bioeconomy
- Capitalize on natural solutions to offset C's footprint
- Develop healthy and sustainable diets and increase the use of alternative protein sources

USDA Blueprint

- Understand the biology of the genome to accelerate the genetic improvement of parameters of economic interest
- Reduce the effects of animal diseases
- Apply the technology of precision agriculture to the phenotyping of animals
- Take advantage of the microbiome to improve the efficiency and sustainability of animal production

Road Map for Sustainable EU Livestock

- Strengthen the role of sustainable animal production in the circular bioeconomy
- Promote the differentiation of production systems based on sustainability as added value
- Promote access to technology
- Promote research on consumer perception and expectations to respond to their demands

Maritime Affairs and Fisheries Strategic Plan 2016-2020

- More sustainable and competitive fisheries and aquaculture by 2020
- A sustainable blue economy generating growth, jobs and prosperity by 2020
- Sustainable fisheries worldwide and improved international governance by 2020

SUMMARY FOR EXPERTS

MINISTERIO DE CIENCIA E INNOVACIÓN

CSIC

Challenge Animal Production

CHALLENGE 6C: COMPREHENSIVE IMPROVEMENT OF LIVESTOCK AND AQUACULTURE SYSTEMS

WHAT

Animal production on land and aquatic systems are key economic, social and environmental sectors in Spain. Animal production is limited by the scarcity of land, food resources and water and the situation will be worse on a scenario of climatic change.

HOW

Facing scientific challenges associated with animal health and welfare, reduction of environmental impact, increasing availability of resources and productive efficiency, improving quality of animal products and adapting production systems to available resources and productive purposes and increased resilience

IMPACT

Generation of biological and technical knowledge and establishment of scientific and technical bases for the development of future animal production systems

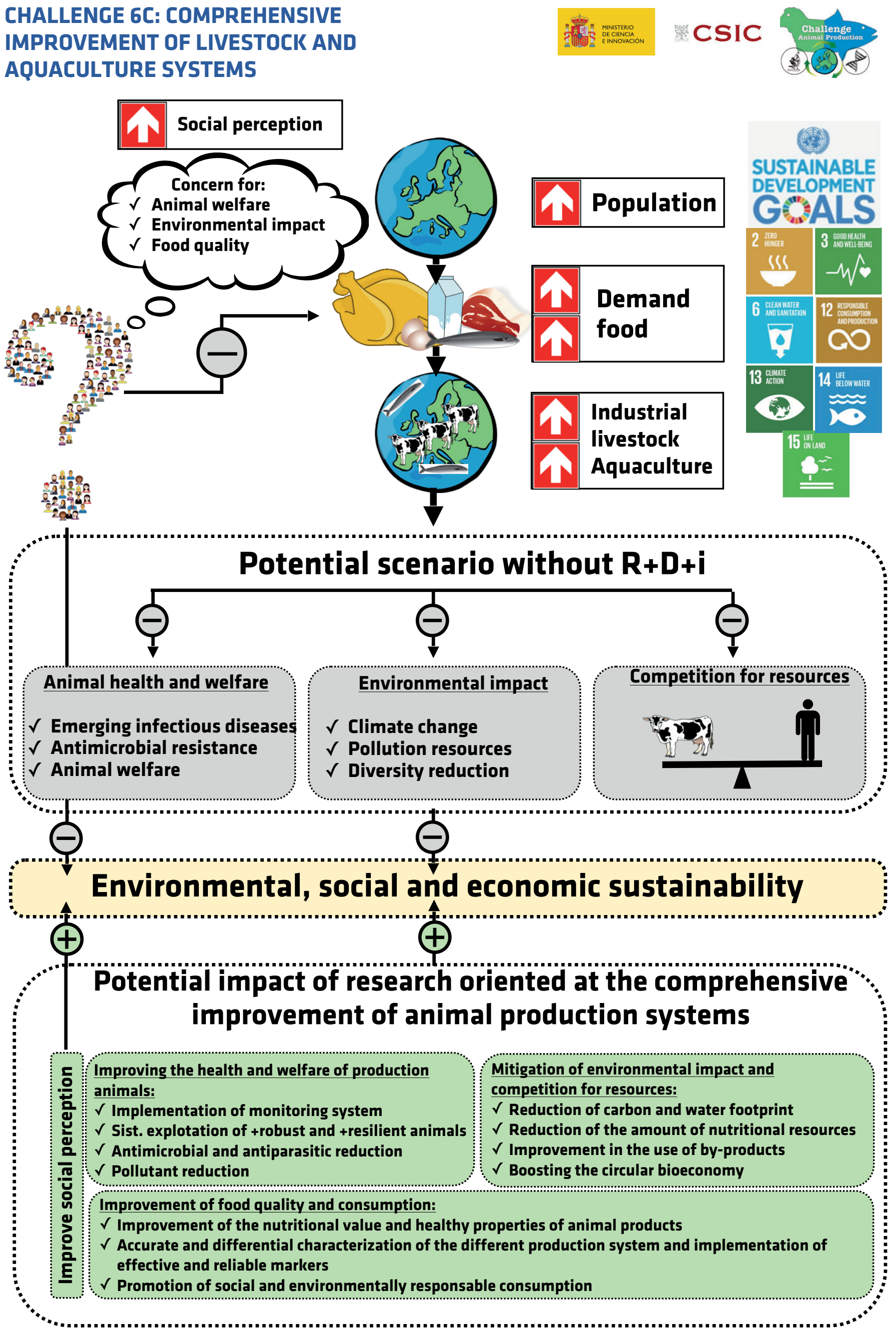
WHO

The community of experts at the CSIC in Nutrition, Livestock Systems and Land Use, Animal and Human Health , Physiology, Genetics, Genomics, Parasitology, Immunology, Monitoring, Conservation and Transformation of Products, Food Security, Ecology, Aquaculture, Biodiversity, Governance Systems in Environmental Management.

SUSTAINABLE DEVELOPMENT GOALS

2 ZERO HUNGER
3 GOOD HEALTH AND WELL-BEING
6 CLEAN WATER AND SANITATION
12 RESPONSIBLE CONSUMPTION AND PRODUCTION
13 CLIMATE ACTION
14 LIFE BELOW WATER
15 LIFE ON LAND

SUMMARY FOR THE GENERAL PUBLIC



CHAPTER 4

ABSTRACT

Every year, different harmful organisms (pests and pathogens) significantly reduce the potential yield of agricultural crops and threaten the sustainability of the planet's forests. At present, this situation is compounded by the harmful effects of climate change. It is essential to generate new knowledge and technologies for a more efficient control and management of strategic diseases and pests that constitute a threat in key productive sectors for the world economy, and in particular the Spanish one.

KEYWORDS

plant health | pests | climate change | emerging diseases | resistance | genome editing | crop production | forest | plant pathogens

CHAPTER 4

PLANT HEALTH. RESISTANCE TO PESTS AND DISEASES

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EXECUTIVE SUMMARY

Plant health is of global importance for sustainable agriculture, food security and environmental protection. To satisfy a growing demand for food, global agricultural production must increase by 70% by 2050. However, main agricultural crops are threatened by pests and diseases that put global food supplies at risk. Rates of introduction of exotic of pests and pathogens are increasing exponentially in recent years, driven largely by altered patterns and increasing rates of travel and trade. Climate change and global trade drive the distribution, host range, and impact plant pests and diseases, many of which can spread or reemerge after having been under control. Indeed, many historical and contemporary diseases are emerging as major threats to modern agriculture and food security. Forests, as main components of natural ecosystems that provide not only important primary resources (timber, resin, cork) but also crucial ecosystem services for the humanity (climate regulation, carbon storage, wildlife support, social use and recreation), are also at unprecedented sanitary risk.

Given this scenario, the present committee sees the following key challenges for the next 10-20 years in the field of plant health: 1. Globalization and increasing impact of climate change in plant health; 2. Control of emerging and re-emerging pests and diseases; 3. Strategic pests and diseases that constitute a threat in the key productive sectors for the Spanish economy; 4. Sustainable management of pests and pathogens resistance to phytosanitary treatments; 5. Achieving broad spectrum immunity through genome editing.

The achievement of the key challenges described in this report will not only provide crops more resilient to different pathogens and pests, but will contribute also to develop robust and sustainable bio-economies while preventing environmental degradation and will likely contribute to empower high technological innovations and further high-impact revolutionary developments. Particularly, both synthetic biology and genome editing will provide the opportunity for developing useful tools to generate more resistant and safer crop plants. A better understanding of different issues described in this challenge compilation will be of clear direct or indirect benefit to the agronomic and forestry sectors.

1. INTRODUCTION AND GENERAL DESCRIPTION

Plant health is of global importance for sustainable agriculture, food security and environmental protection. To satisfy a growing demand for food, global agricultural production must increase by 70% by 2050. However, main agricultural crops are threatened by pests and diseases that put global food supplies at risk. Accurate information on the extent of losses from pests and disease is difficult to estimate but 30-40% losses in developing countries annually from 'field-to-fork' are common (Flood, 2010). More specifically, yield losses caused by pests and diseases are estimated to average 21.5% in wheat, 30.0% in rice, 22.6% in maize, 17.2% in potato, and 21.4% in soybean; these crops account for half of the global human calorie intake (Carvajal-Yepes et al., 2019). According to the latest estimates from the Food and Agriculture Organisation of the United Nations (FAO), 840 million people, 12% of the global population, were unable to meet their dietary energy requirements (http://www. fao.org/publications/sofi/en), with even greater numbers lacking minimal requirements of essential vitamins and minerals. Previous European Union (EU) agricultural policy had focused on constraining food production but there is a new understanding that the EU should now increase its biomass production for food, livestock feed and other uses, including renewable materials to support the bioeconomy. Agriculture will face in the near future major challenges to deliver food and nutrition security at a time of increasing pressures from climate change, social and economic inequity and instability, and at the same time facing the continuing need to avoid further losses in biodiversity and ecosystem services.

Rates of introduction of exotic pests and pathogens have increased in recent years, driven largely by altered patterns and increasing rates of travel and trade (Brasier, 2008). Under the present constraints of limited availability of arable land, climate change, increased seasonal weather instability, and intensive global trade, the threat posed by plant pests and diseases to humankind may become even more serious, particularly because these conditions favor the emergence or re-emergence of harmful organisms that have high impact. Many historical and contemporary pests and diseases that were under control are now reemerging as threats to modern agriculture and food security. The European Food Safety Authority (EFSA, 2012) states that emerging risks can result from: i) a newly identified plant threat for which a significant probability of introduction and geographical spread may occur; ii) an unexpected new or increased probability of introduction or spread of an already known agent, for example as a consequence of new trade or new agricultural policy and iii) a new or increased susceptibility of host plants to a known agent or to an agent with altered virulence (including development of resistance to previously effective control measures mainly of chemical nature) or extended host range. Tackling the issue of existing, evolving as well as invasive insect and pathogen species is of crucial importance as they are a major threat to plant health and are considered to be one of the main direct drivers of several detrimental effects on biodiversity, human and animal health, and crop production.

Forests, as main components of natural ecosystems that provide not only important primary resources (timber, resin, cork, etc.) but also crucial ecosystem services for the humanity (climate regulation, carbon storage, wildlife support, social use and recreation), are also at unprecedented sanitary risk (Trumbore et al., 2015). Recent anthropogenic influences such as climate warming, drought intensification, wildfires and the continuous expansion of new pests and pathogens beyond biogeographical regions, are dramatically challenging the resilience of natural and planted forest, riskily pushing some forest ecosystems to a point of no return (Seidl et al., 2017). Prevention, mitigation and management of forest health decay is a main challenge for the scientific community, especially given the intrinsic complexity of forest ecosystems and the difficulties associated to their investigation and management. Both the large spatial and temporal scales of forest ecosystem impose conceptual questions and methodological challenges that need to be addressed. Research must do a stronger effort to combine long-term time series of forest monitoring, broad-scale tools (e.g. remote sensing) for landscape-scale health assessments, and mechanistic fine-scale investigations in order identify the drivers of forest decay, how they interact and the recovery trajectory of forest functioning. Concomitantly, the low profitability of forest systems and their environmental context prevent the use of intensive phytosanitary tools, making the search of alternative environmentally-friendly and cost-effective ways to preserve forest health an urgent need. Finally, while for agricultural crops, yield and crop quality are clear objectives to be pursued, forest ecosystem health needs a more holistic definition, in which fundamental attributes of forest ecosystems (e.g. species biodiversity, soil protection, vegetation structure, carbon and nutrient cycling) must be considered (Millar and Stephenson, 2015).

Given this scenario, the present committee identifies the following key challenges for the next 10-20 years in the field of plant health:

1. Globalization and increasing impact of climate change in plant health
2. Control of emerging and re-emerging pests and diseases
3. Strategic pests and diseases that constitute a threat in the key productive sectors for the Spanish economy
4. Sustainable management of pests and pathogens resistance to phytosanitary treatments
5. Achieving broad spectrum immunity through genome editing

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

Currently, our society demands longer, healthier and safer life. Plant health has a relevant role that must be promoted and sponsored by the corresponding public authorities. Existing a close linkage between plant health, food security and societal stability, the spread of plant pests and diseases among crops and forests, has significant global consequences for farmers, the seed industry, policy-makers, the general public, and the environment and landscape.

Research in plant health has contributed to science in a broader way, beginning with the work of the plant pathologist Anthony de Bary, and others, who helped to establish the germ theory of disease. This served as the foundation for innovations that improved the human condition by establishing the etiology of diseases affecting people and also by limiting the impact of plant pathogens on the food supply. Other significant contributions of basic science in plant health have been the identification of bacteria and viruses as disease-causing agents, demonstration of RNA as a genetic molecule, and the discovery of novel phenomena such as the autocatalytic properties of the RNA, the ice-nucleating bacteria and RNA silencing (Fraenkel-Conrat and Williams, 1955; Lindbo and Dougherty, 2005; Lindow et al., 1982).

The achievement of the key challenges described in this report will not only provide crops more resilient to different pathogens and pest, but will contribute also to develop robust and sustainable bio-economies while preventing environmental degradation and will likely contribute to empower high technological innovations and further high-impact revolutionary developments. Particularly, both synthetic biology and genome editing will provide the opportunity for developing useful tools to generate more resistant and safer crops. A better understanding of the different issues described in this challenge compilation will be of clear direct or indirect benefit to the agronomic and forestry sectors.

3. KEY CHALLENGING POINTS

3.1. Globalization and increasing impact of climate change in plant health

Climate change and globalization act as main drivers of the increasing sanitary risks. The complex nature of plant-pathogen and plant-pest interactions make difficult to predict the impacts on crop yields and quality due to changes in climate, as well as to generalize the appropriate strategies to minimize them. Outcomes of climate change in plant pathosystems include, among others, modifications in host resistance, altered stages and rates of pathogen and pests (including vectors) development and changes in the physiology of host-pathogen-vector interactions. Likewise, climate change may have a direct effect on the phenology and physiology of both host and pests, as well as indirect effects on the interaction of pests with their hosts, natural enemies and competitors. These effects have been predicted to result into shifts in the geographical distribution of hosts, pathogens and pests, changes in pest and disease incidences and severity of damage, altered crop losses due to harmful organisms and modifications in the efficiency of management strategies (Canto et al., 2009; Sharma, 2014; Jones et al., 2016; Forrest, 2016).

Despite the efforts in the last decades to prevent biological invasions, agricultural pests and pathogens continue to spread at unprecedented rates (Strange and Scott, 2005; Dehnen-Schmutz et al., 2010). The extent and speed at which the geographical distribution of pest and pathogens is spreading is determined by the processes that facilitate their dissemination to new areas (e.g. global trade), favored by extreme climatic events and by the ability to survive in them that is determined primarily by the minimum winter temperatures. Between 2010 and 2015, ProMED (http://promedmail.org) has listed approximately 140 new records of plant pests and pathogens. Most common are reports of newly arrived viruses and viroids (36.6%), followed by fungi (28.2%). ProMED reports primarily on infectious diseases, including plant-pathogenic nematodes, and thus new reports of insect pests are rare. The majority of new observations are in the Northern Hemisphere, although several records are from Australia. The most commonly affected crops are maize (9.1%), bananas (8.5%), citrus (7.7%), and potato (7.0%) (Bebber, 2015), while almost all forest systems are at risk (Santini et al., 2013).

The effects of variations in climate on cycles of pests and pathogens are influenced by the effect of such variations on crop development. Available information suggests that the elevated CO2 (eCO2) in the atmosphere will increase the plant photosynthetic rate, but the extent of the increase will depend on the levels of other environmental factors such as temperature or relative humidity, plant type (C3 or C4), or irrigation efficiency.

The increase in temperature projected by climate models can favour shorter reproductive and infection/infestation cycles by plant pathogens and pests, as well as an increase in their reproduction rate. Both effects can operate in favour of the evolutionary potential and virulence gain processes of plant pathogens, which may be associated with both the increase in the size of the resulting populations and the highest expectation of survival of such populations between crop stations. Pests, including those that comprise the main groups of virus vectors such as aphids, whiteflies, cycads and thrips, are very sensitive to changes in temperature, wind and precipitation. The likely increase in winter temperatures in the coming years will modify the biological cycle and behavior of these insects, as well as their ability to expand to other geographic regions. Since 1960 there has been a displacement of more than 600 pests and diseases towards the poles at an average of 2.7 km / year (Bebber, 2015). Also, changes in the temperature regime alter the plant´s physiology affecting the two better-known types of antiviral resistance mechanisms, those based on RNA interference and dominant resistances based on protein-protein recognitions (Canto et al., 2009). Other interactions with stress response pathways in plants may also have consequences for disease expression and progression.

Pest and pathogen control will be foreseeably more complicated, due to the difficulties to predict the response of pest, pathogen and vector populations to the physiological alterations of the plants and the changes in ecosystem functioning that may have effects on host susceptibility. On the positive side, we must count on recent technological advances that have improved significantly our ability to react. For example, the use of high throughput sequencing is greatly facilitating the discovery of the etiology of new diseases, and is providing the information necessary to design effective and affordable detection tools. Similarly, advances in breeding technologies for cultivated plants, including genome editing, are providing responsiveness in terms of genetic improvement never before experienced.

Challenges

It is crucial to intensify research on globalization, climate change and their consequences. Over the past few years, some notable shortcomings have been corrected, but many aspects remain poorly explored. The effects of the most important parameters (essentially temperature and eCO_2) have been studied in detail for a certain number of systems, but there are other parameters little studied, including the effect of greenhouse gases other than CO2, the effect of increases or decreases in precipitation, relative humidity and unusual events such as tornadoes, floods, extreme droughts or massive wildfires. On the other hand, real situations are complex, and therefore future lines of research should intensify the study of factors —both biotic and abiotic— combined, under controlled experimental but also upscaling to situations closer to reality. Additionally, it is essential to advance in the modeling of trade and climate change scenarios in relation to the emergence, incidence and severity of pest and pathogens, both for medium- and long-term predictive purposes and to help in the application of short- and medium-term control strategies.

3.2. Control of emerging and re-emerging plant pathogens and pests

Emerging and re-emerging plant infectious diseases and pests are major threats to food security. Their incidence increases due changes in the epidemiology frequently associated with invasion of new pest or pathogen populations, and their impact might be particularly severe. Alteration of the equilibrium between harmful organisms and host plants present in natural ecosystems results into the emergence or re-emergence of pests and diseases. Human activity facilitates new damaging encounters between plants and pathogens-pests. Moreover, the alteration of plant landscapes (e.g. widespread cultivation in monocultures, introduction of new plants or new plant genotypes) or the intensification of global trade of plants and plant products increases the instability favouring emergence of pests and diseases. Furthermore, climate change is also severely modifying co-evolved equilibrium, potentially leading to increased problems associated to harmful organisms of plants. Epidemiological theory predicts that the emergence of new pests and diseases is the result of complex interactions among these multiple factors. Diseases and pests reduce global agricultural production by about 10-15% each, and the highest losses often hit food-deficit regions with fast-growing populations where frequently emerging or re-emerging problems occur. Understanding the processes that lead to the emergence or re-emergence of pathogens and pests would help preventing the serious agricultural problems that they pose.

In this scenario, plant health practices should help to guarantee food security and safety. For that, pest and pathogen control measures are required to prevent crop yield losses. The European legislation promotes the use of control methods that are environmentally friendly and respectful with human health, and aims to implement Integrated Pest Management (IPM) strategies (EC, 2020). Sustainable biological, physical and other non-chemical methods must be preferred to chemical methods, and the pesticides applied shall be as specific as possible for the target and shall have the least side effects on human health, non-target organisms and the environment. However, resistant crop varieties, biocontrol agents and/or pesticides efficient against key pests are not always available, especially for those recently introduced. The development and improvement of novel technologies (e.g.- pest resistant varieties generated by CRISPR/Cas and other editing technologies, microbiome-primed plants, geolocation and molecular tools for pest monitoring, remote sensing technics for early detection, mathematical modelling for the establishment and spread, IPM, etc.) are expected to have an impact in the near future. In addition, the complexity of agroecosystems, together with the threats derived from climatic change and the growing social demands relative to food security emphasize the need of generating basic knowledge and its transference to the productive sector.

Emerging exotic pests and diseases are of particular relevance in forest systems. While native antagonists co-habit with natural forests in a dynamic equilibrium and rarely cause alarming outbreaks, exotic pests and diseases, once established into a new geographical range, may cause devastating effects on forest ecosystem functioning. The Dutch elm disease and the ink disease of chestnuts are good examples of how exotic invaders may decimate native forests when expanding to new habitats. Many other pests and diseases are nowadays initiating its spread across Iberian forests posing unprecedented problems to many if not all native forest trees. Lack of natural enemies and lack of efficient resistance mechanisms may be behind the high susceptibility of native forests to these imported enemies. However, knowledge on these newly established interactions is still very limited. As natural extensively-managed systems with low economical return, research efforts for improving early diagnosis and large-scale monitoring, fine-tuning integrated management control, management actions that favor resistance enhancement or minimize the impact of damage on tree fitness (tolerance) and assessing long-term and broad-scale impacts in ecosystem services are urgently needed.

Challenges

- Improve approaches and large-scale methodologies for pests and pathogen surveillance and diagnosis aimed to facilitate the rapid implementation of contingency plans.

- Fine-tune methods for landscape-scale assessment of agricultural and forest health, in general, and incidence of exotic enemies, in particular, using remote sensing tools.
- Understanding factors driving emergence and evolution of pathogens and pests. Modelling and forecasting.
- Improve the mechanistic understanding and the ecophysiological basis of the high susceptibility of the native flora to alien enemies.
- Insights into global warming as driver of the emergence or re-emergence of pests and diseases.
- Enlarge the range of tools for integrated, sustainable and effective management of emerging and re-emerging pests and diseases.
- Understanding the impact of emerging and re-emerging harmful organisms on crops, wild plant communities, and the ecosystem services they provide.

The expected impact will be obtaining adequate responses to emerging disease or pests that may cause agricultural problems. In the longer term, acquired knowledge will help the agricultural/forestry sector to remain productive and contribute to agriculture sustainability and/or forest health. Adequate management of emergent pests and diseases will help to avoid large-scale transformation in the landscape and maintain socially valued ecosystem services of forests. Major needs should be solved to attain the challenges, especially increasing investment in: i) biosecurity containment facilities and specialized personnel to work with exotic and quarantine pathogens and pests; ii) permanent positions for highly qualified young scientists that could integrate different approaches and research disciplines; iii) permanent positions for qualified lab technicians; and iv) singular equipment shared in network frame (such as large scale phenotyping and genome sequencing platforms, etc.).

3.3. Strategic diseases and pests that constitute a threat in the key productive sectors for the Spanish economy

As indicated in previous sections, the threats posed by re-emerging or new plant pests and diseases are now greater than ever. The number of plant pests establishing in Europe has been predicted to increase significantly in the next 10 years based on current trends (EU project DAISIE at www.europe-aliens.org). Recently, the European Commission established a list of 20 priority quarantine pests (EC, 2019), based on their potential economic, environmental or social impact in respect of the EU territory. The purpose of this chapter is not to provide a detailed revision of all the harmful pests and pathogens (quarantine and indigenous) that currently pose a threat to Spanish agriculture and forestry, but to focus on those for which the CSIC is playing or may play a crucial role on gaining basic knowledge and contributing to develop innovative management approaches for minimizing their impacts.

3.3.1. Main pest of agriculture and forest Iberian systems

Indigenous pests, either endemic or immigrant species that have been established for a long time in our country, constitute a persistent threat for some key productive sectors. Examples of this type of pests in our country are the Mediterranean fruit fly, *Ceratitis capitata,* for fruit trees and the *aphids Myzus persicae* and *Aphis gossypii* for vegetable crops, though there are many others. In addition to these prevalent pests, some of the threats that have raised the most serious concerns in the last years correspond to recently introduced exotic species, such as the red palm weevil, *Rhynchophorus ferrugineus,* or the tomato moth, *Tuta absoluta*. In the EU priority quarantine list (EC, 2019), a total of 16 pests of vegetable, arable and fruit crops and forest trees has been included: fruit flies (*Anastrepha ludens, Bactrocera dorsalis, B. zonata Rhagoletis pomonella*), curculionids (*Anthonomus eugenii, Conotrachelus nenuphar*), lepidoptera (*Spodoptera frugiperda*, *Thaumatotibia leucotreta, Dendrolimus sibiricus*), psyllid (*Bactericera cockerelli*), and six coleopteran (*Aromia bungii, Popillia japonica, Agrilus anxius, A. planipennis, Anoplophora chinensis, A. glabripennis*). Additionally, other exotic pests not included as EU priority pests such as *Leptoglosus occidentalis* in stone pine orchards or *Dryocosmus kuriphilus* on chestnuts are all causing or are predicted to soon cause serious problems in Iberian forests. Finally, although some pests do not cause significant direct feeding damage *per se,* they are vectors of important plant pathogens (mainly virus and bacteria).

3.3.2. Main pathogens in agricultural and forestry Spanish systems

In Spain, besides native pathogens that have affected or continue affecting strategic crops causing severe diseases and important yield losses, at least half a hundred of new pathogens have been introduced, and other pathogens are spreading or increasing in virulence promoting the emergence and reemergence of plant diseases. Among those pathogens threatening the Spanish agricultural and ornamental plant sector include: 1) oomycete and fungi (diverse *Aspergillus* spp. and *Fusarium* spp. producing mycotoxins, *Botryosphaeria* spp., *F. mangiferae, F. oxysporum* f. sp. *basilici*, *F. solani* f. sp. *cucurbitae* race 1, *F. sterilihyphosum, Monilinia fructicola, Mycosphaerella nawae, Phytophthora* *hedraiandra, P. tentaculata, Verticillium dahliae,* several fungi causing grapevine trunk diseases); 2) bacteria and phytoplasmas (*Candidatus* Liberibacter *solanacearum, Clavibacter michiganense* pv. *sepedonicus, Curtobacterium flaccumfaciens* pv. *flaccumfaciens, Erwinia amylovora, Pseudomonas viridiflava, Ps. syringae* pv. *actinidae, Ralstonia solanacearum, Xanthomonas arboricola* pv. *pruni, X. vesicatoria, Xylella fastidiosa*, Flavescence dorée or 'Stolbur'); 3) several viruses and viroids (e.g., Cucumber green mottle mosaic virus (CGMMV), Citrus Tristeza Virus (CTV), Cucumber vein yellowing virus (CVYV), Cucurbit yellow stunting disorder virus (CYSDV), Sharka of stone fruit trees (PPV), Tomato chlorosis virus (ToCV), Tomato torrado virus (ToTV), Tomato brown rugose fruit virus (ToBRFV), begomovirus etc.); and 4) nematodes (*Aphelenchoides besseyi,* several *Meloidogyne* spp. on fruit trees). Among those pathogens, the nematode, *Bursaphelenchus xylophilus* and the bacteria *Xylella fastidiosa* and *Candidatus* Liberibacter spp., are listed as priority pests for Europe (EC, 2019).

There are several outstanding examples of pathogens threatening Iberian crops, among which some of them deserve special attention due to the dramatic economic consequences that its entrance or spread could cause to Spanish agriculture, or because there are several CSIC's research groups working on them: 1) Huanglongbing (HLB) or Citrus greening disease caused by *Candidatus* Liberibacter spp. is considered the most devastating citrus disease worldwide. The lack of resistant citrus varieties and economically feasible treatments for infected trees, and absence of durable control mechanisms makes HLB disease a threat to more than 516 million trees throughout the EU. The African citrus psyllid, *Trioza erytreae,* that transmits HLB, has recently been found in northwestern Iberian Peninsula (Spain and Portugal) with increases the threat that HLB poses to the Spanish citriculture. 2) In Europe, *X. fastidiosa* has emerged as a pathogen of global importance associated with a devastating epidemic in olive trees in Italy in 2013. But since then, several other outbreaks were discovered in the EU, affecting other important economic crops such as grapes and almonds in Spain, but also species of cultural/patrimonial importance, landscape and ornamental plants. These outbreaks evidence that major EU crops can be severely damaged by *X. fastidiosa* infections, affecting not only EU agricultural productivity but the environment and cultural heritage (e.g., Over €5.5 billion in agricultural production could be affected annually and nearly 300,000 jobs involved in olive, citrus, almonds and grapes production could be at risk if *X. fastidiosa* becomes widely spread in the EU; EFSA, 2018). 3) Verticillium wilt of olive caused by the soilborne fungus *V. dahliae* is currently considered the main soilborne disease threatening olive production worldwide, and is becoming an increasing concern in olive production because is causing devastation in young and old olive orchards in different regions of Andalusia, with a prevalence on those areas higher than 40%, and is also spreading to all other major olive-growing areas of our country. 4) Several fungal species belonging to the Botryosphaeriaceae are becoming important emerging diseases mainly damaging stone and pome fruits, olive, walnut and avocado in many countries including Spain (e.g., 70-90% loss has been reported in olive trees; Moral et al., 2019), which highlight the need for a focus on these pathogens. 5) Global spread and increase of populations of whiteflies as a result of climate change and changes in agricultural practices is resulting in the emergence or re-emergence of whitefly-transmitted viruses that severely damage economically important crops, including DNA viruses of the genus *Begomovirus* and RNA viruses of the genera *Crinivirus, Ipomovirus,* and *Torradovirus* which are associated to severe outbreaks, such as CVYV, CYSDV, ToCV and ToTV and for which no effective control is always available (Navas-Castillo et al., 2014). 6) Several Tobamovirus have re-emerged in the last few years causing important problems such as CGMMV in cucurbits and ToBRFV in tomato, probably due to their extreme persistence and infectivity, global seed and fruit trade and the widespread use of tolerant varieties (Dombrovsky et al., 2017). 7) Sharka disease caused by PPV is one of the most devasting *Prunus* spp. diseases, which causes a high percentage of apricot and plum EU production being unmarketable every year. The costs of sanitary controls, surveys and eradication programs against PPV worldwide in the last 30 years exceeds 10,000 million euros (Cambra et al., 2006).

As occurring for strategic agricultural crops, the most problematic and concerning sanitary risks of temperate forests are those originated by exotic invasive species to which native or planted trees lack efficient resistance and tolerance mechanisms (Wingfield et al., 2015). Most, if not all, native forest species in the Iberian Peninsula are or will be soon threatened by exotic organisms, some of which are already causing devastating damage and large-scale transformations in our forest systems. Exotic pathogens such as *Bursaphelencus xylophilus, Pestalotia stevensonii* or *Fusarium circinatum* on pines, several *Phytophthora* spp. (including *P. ramorum* on oaks and *Phytophthora alni* in alders), *Hymenoscyphus pseudoalbidus* on ashes, *Cryphonectria parasitica* on chestnuts and *Ophiostoma novo-ulmi, Brenneria quercina* are all threathening Iberian forest. Although is not easy to select one harmful organism as the most relevant for Iberian forest, considering the vast area occupied by the iconic oak open lands 'dehesas' in the Iberian Peninsula (ca. 7 Mha), their high environmental and social value and their strong link with humans since ancient times, we stand out the oak decline as one of the most dramatic forest health problems currently affecting Iberian forests. Although other pathogens may be involved, chronic root pruning by the oomycete *Phytophthora cinnamomi,* an alien invasive species widely distributed in Iberian soils, appears to be the main biotic trigger of oak decline. The extent of oak decline is not yet well known, but by 2010, 8000 ha of holm oak stands were estimated to be being lost annually only in Spain, and climate projection models forecast even a worse scenario in the near future.

3.4. Sustainable management of pests and pathogens resistance to phytosanitary treatments

Plant protection products (PPP) include synthetic pesticides derived from a chemical synthesis or biopesticides, from a biological origin (animals, plants, bacteria, minerals, etc). The number of PPPs used has doubled since 1980. However, more and more synthetic PPP are being banned due to environmental and human health concerns and the development of new conventional (synthetic) PPPs has decreased significantly. In contrast, the number of biopesticides has increased in the last decades (EPRS, 2019). The effectiveness of pesticides is threatened by the evolution of harmful organisms resulting in resistant pathogens, weeds, or pests (Hawkins et al., 2018).

Pesticide-resistant individuals are natural variants selected by intensive application of PPP that carry genetic (i.e., nucleotide polymorphisms) or epigenetic modifications leading to biochemical, physiological, and ultimately phenotypic differences (R4P Network, 2016). Strategies should be implemented for a correct manage of resistance in order to prevent or at least slow down the accumulation of resistant individuals in pest populations and to preserve the effectiveness of available pesticides (FAO, 2012). The major resistance management strategies currently recommended for all types of pesticides include the use of a mixtures of pesticides with different modes of action or resulting in different resistance mechanisms and rotations or alternation of pesticides to avoid single sense selection processes. Specific resistance management strategies have been developed for the various fungicide chemical groups such as: i) implement integrated disease (pest) management (IPM); ii) restrict the number of treatments per season, iii) applying pesticides only when strictly necessary; iv) use low effective (recommended) doses; or v) avoid eradicant (biocides) uses. For durable insecticides managements, tactics include i) the avoidance of overuse of a single insecticidal mode of action; ii) avoidance of generic insecticides focusing on a single crop-pest combination; iii) use in the frame of integrated pest management (IPM) approaches; iv) protect beneficial organisms; v) rotate unrelated compounds; vi) use of mixtures with caution; and vii) monitor problematic pest to detect first shifts in sensitivity (FAO, 2012). Accurate, sensitive and reliable tools for both monitoring and modelling of pesticide resistance are critical for the correct implementation of resistance management strategies (Kole et al., 2019).

As an alternative to synthetic PPP, biopesticides and related alternative management products are increasingly used. Third-generation pest control agents reduced the risk of synthetic pesticides, and biobased pesticides is a term that is increasingly used interchangeably with biopesticides. New tools, including semiochemicals and plant-incorporated protectants (PIPs), as well as botanical and microbially derived chemicals, are playing an increased major role in pest management (Seiber et al., 2014). Ideally these products are target-specific, with low toxicity to nontarget organisms, reduced in persistence in the environment, and potentially usable in organic agriculture (Seiber et al., 2014). Most of the biopesticides, especially the microbial products, have multiple modes of action and usually do not target a single site or gene, thus reducing the risk of development of resistance (Dimock and Ockey, 2017).

Challenges

- Improve the sustainability of crop production through the intensification in the implementation of IPM systems, coping the reduction of phytosanitary products by combining the new technologies, precision farming, or development of resistant varieties by means of classical and new breeding techniques.
- Combine the development of accurate laboratory pest monitoring techniques with field monitoring to provide useful on-time guidance to growers.
- Effective application of theoretic modelling to environmental conditions present in field populations to minimise resistance risk.

Impact of research

Basic and applied research on sustainable use of pesticides based on the understanding of the mechanisms underlying the development and evolution of resistance in target harmful organisms will have a great impact on durable control of pests and pathogens and then on food security and environmental protection.

3.5. Achieving broad spectrum immunity through genome editing

Breeding crops for resistance to pests and diseases has tended to be a lower priority than breeding for yield and quality when control chemicals have been available. Traditionally, growers use chemical compounds to reduce the disease incidence in crops. Conversely, new environmental concerns, chemical safety of growers and the emergence of different resistance mechanisms from pathogen are reducing the use of pesticides and their applications (Gullino and Kuijpers, 1994). The new European Union guidelines aimed to progressively limit the use of chemical compounds are forcing to join efforts to achieve more durable resistance to pathogens and pests trough new molecular approaches.

The development of ‘omic’ technologies has revolutionized studies and approaches in Plant Pathology and in other areas of Plant Biology. But the technique that will have a greater impact on plant health in the coming years is undoubtedly that based on the clustered regularly interspaced short palindromic repeats (CRISPR)/Cas technology. This technology is the more accessible alternative for genome editing of eukaryotes described until now. Genome editing has radically shake-up the biological world by providing a means to edit genomes of living organisms, including humans, plants, animals, and microbes. The CRISPR/Cas system can induce sequence-specific mutagenesis to alter or modulate genes and that can be used for trait improvement in crops. CRISPR/Cas has the potential to make more robust and efficient crops, more resilient to climate change alterations (Zhang et al., 2019). Robustness of CRISPR/Cas and specially its versatility and accessibility have made it possible that in a few years it has become a very promising tool for generating resistance against plant pathogens and pests.

CRISPR/Cas-based technologies have successfully been used for improving resistance to fungal, bacterial and viral pathogens (Borrelli et al., 2018). The main strategies employed in model species such as *Arabidopsis thaliana* and *Nicotiana benthamiana*, include the integration of CRISPR-encoding sequences that target and interfere with the pathogen genome. Also, CRISPR/Cas can be used to mediate targeted mutations in the host plant genome to increase resistance. In most of the cases these have been achieved by targeting a single locus. One of the most promising capabilities of this technology is the possibility of acting on different loci at the same time. Thus, for example, Zsögön et al. (2018) were able to *de novo* domesticate wild tomato plants, *S. pimpinellifolium*, by targeting a set of six key genes using a multiplex CRISPR/Cas9 approach to generate loss-of-function alleles. Multiplex genome editing in plants initially focused on input traits such as herbicide resistance, but has recently been expanded to hormone biosynthesis and perception, metabolic engineering, plant development and molecular farming, with more than 100 simultaneous targeting events reported (Najera et al., 2019).

CRISPR/Cas has successfully been used to confer resistance/tolerance against single important fungal, bacterial and viral diseases (Chen et al., 2019). A future challenge will be to evaluate the feasibility of the CRISPR/Cas-based approaches for engineering broad-spectrum resistance against multiple pathogens and pests. The main limitation to deploy genome-edited crops in the fields rely on the legal and procedural uncertainties regarding the status of genome edited crops in Europe. While the CRISPR/Cas technology is being adopted at an unprecedented speed, the current regulatory framework remains outdated. Moreover, the European Court of Justice (ECJ) ruling from 2018 (C-528/16) brought even more confusion because of the interpretation that crops obtained by precision breeding are subject to the GMO regulatory provisions. The network EU-SAGE[1] was launched. aiming to provide information about genome editing and to promote the development of European and EU member state policies that enable the use of genome editing for sustainable agriculture and food production.

Impact

Although multiplexed CRISPR/Cas-based approaches have been already described, their routine and extensive implementation is limited by important technological developments. One that can be worth highlighting is the way in which the different ribonucleoprotein complexes are delivered to the plant, avoiding genetic transformation. Research in this area will require a significant progress in single-cell genomics and transcriptional profiling. These technological advances may reveal molecular details of pathogen restriction, cell autonomous and non-autonomous pathogen responses, and the influence of environmental factors and host developmental stage on pathogen infection.

1. EU-SAGE is a network representing 131 European plant science institutes and societies that have joined forces to provide information about genome editing and promote the development of European and EU member state policies that enable the use of genome editing for sustainable agriculture and food production. This network is coordinated by Prof. Dr. Dirk Inzé, Science Director at VIB-UGent Center for Plant Systems Biology.

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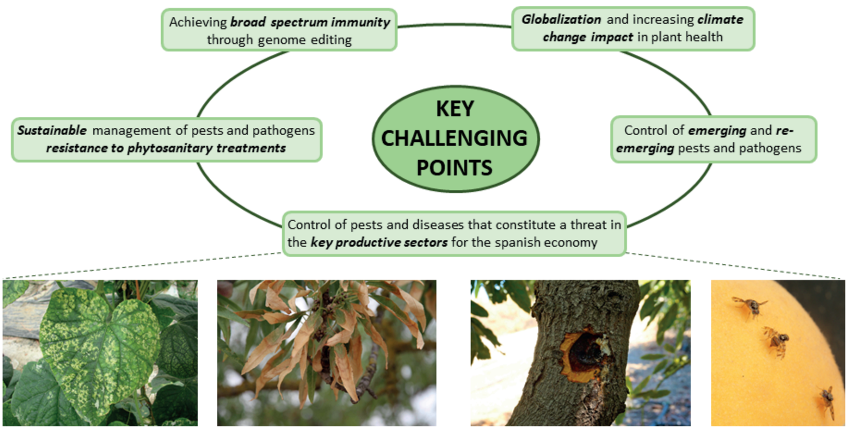
SUMMARY FOR EXPERTS

PLANT HEALTH – Resistance to pests and diseases

Pests and ***pathogens*** under a ***changing climate*** reduce crop yields and threaten forests' sustainability. → Need to develop ***new knowledge*** and ***technologies*** for a more efficient control of pests and diseases.

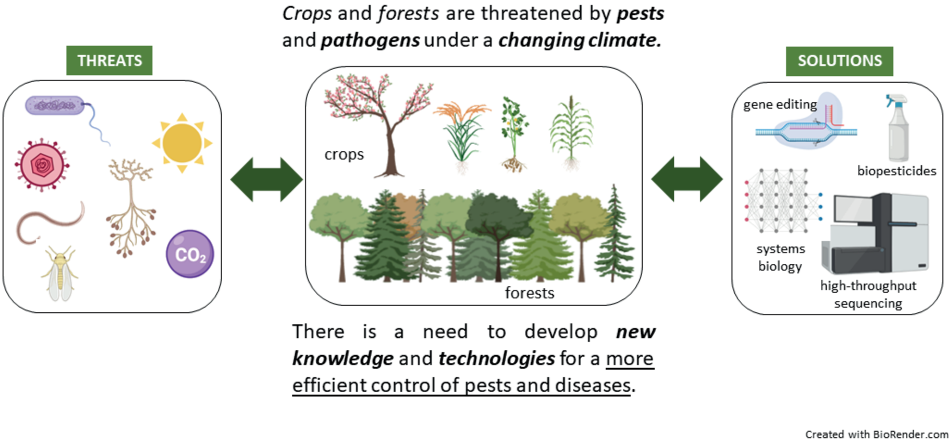


Cucumber green mottle mosaic virus in cucumber (Almería, Spain) | *Xylella fastidiosa* in almond tree (Mallorca, Spain) | *Botryosphaeriaceae* spp. in avocado tree (Málaga, Spain) | *Ceratitis capitata* in peach fruit (Madrid, Spain)

SUMMARY FOR THE GENERAL PUBLIC

PLANT HEALTH – Resistance to pests and diseases

Plant health is of global importance for sustainable agriculture, food security and environmental protection. To satisfy a growing demand for food, global agricultural production must increase by 70% by 2050.



CHAPTER 5

ABSTRACT

The challenge "Biotechnology and Plant Breeding" aims to understand how 'omics information translates into phenotypes in photosynthetic organisms, to turn plant breeding into a predictive science. In scenarios of population growth and climate change, this knowledge will predict the agronomic value of natural variation and spontaneous or induced genetic changes, thus enabling the development of new crops with enhanced features that contribute to increase food security and the sustainability of primary production.

KEYWORDS

biodiversity | phenotyping | genome-editing | synthetic biology | climate change | population growth | omic technologies

CHAPTER 5

BIOTECHNOLOGY AND PLANT BREEDING

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EXECUTIVE SUMMARY

The goals of biotechnology and plant breeding are to deliver new products to maintain food security, and to foster sustainable industrial uses of photosynthetic organisms. The biggest challenges currently facing Biotechnology and Plant Breeding are climate change and population growth, and both require the development of new plant varieties. Whereas traditional breeding objectives are still valid, i.e. higher yield, healthier products, multiple pest resistances, new targets such as adaptation to increased CO_2 levels or elevated temperatures, need to be added. To tackle these challenges, the progress experienced in biological sciences has equipped us with powerful data-gathering techniques, the high throughput ‘omics technologies, supported by unprecedentedly capable bioinformatic approaches, and groundbreaking biotechnological tools, particularly genome-editing and synthetic biology. Using these technologies in model and crop plants, and exploiting the untapped local genetic variability in Spain, will allow us to boost Biotechnology and Plant Breeding for the generations to come. Expected outcomes are the discovery of genes and metabolic pathways that confer resilience to crops against climate change; new varieties, more productive, and of high-quality; the consolidation of plants and algae as biofactories; and the effective dissemination of genome-editing techniques among decision-makers and the general public.

As evidenced in the recent Covid 19 crisis, our country can not afford technology dependence to occur, particularly areas such as food production and

medicines. The CSIC starts from a privileged standpoint for alleviating such dependency, holding a leadership position in Biotechnology and Plant Breeding at the EU and international level. First, CSIC has nationwide deployment, with institutes in different agro-climatic regions, and research groups of excellent international relevance. Second, Spain is one of the richest countries in Europe in genetic resources, such as cereals, legumes and fruits, all strategic crops worldwide. To ensure CSIC leadership, in the first place we propose the creation of the *Biotechnology and Plant Breeding Network* (BPBN) to ensure a proper coordination, collaboration and management of facilities and research groups in the area. In addition, new high throughput phenotyping, genome-editing and synthetic biology facilities, with powerful bioinformatics nodes covering a wide range of expertise, will be required for integrating and translating the information into the agricultural varieties of the future.

1. INTRODUCTION AND GENERAL DESCRIPTION

Biotechnology and Plant Breeding endeavours to deliver plant varieties to ensure food production, make agriculture more sustainable, reduce greenhouse gas emissions, and support other agriculture-related sectors. Biotechnology and Plant Breeding confront two fundamental problems: global population growth (Godfray et al., 2010) and climate change (Wheeler and von Braun, 2013), which will impact world agriculture, dramatically endangering food security. The pipeline of actions to attain a new variety or a new crop is a long one. It starts, inescapably, with basic science, needed to discover the functioning of the machinery of life; continues with the use of the principles of biology and the tools to mine and exploit natural genetic resources, or improve upon them; it makes the developed resources available to breeding in a stepwise manner through pre-breeding; and finally, obtains improved varieties using again genetic and biotechnological approaches. Investment in Biotechnology and Plant Breeding pays off to society in many ways. A study on breeding for arable crops in the EU concluded that measurable positive impacts occurred in increasing social welfare, improving industries related to the agricultural value chain, providing access to affordable food, stabilising agricultural commodity markets, adding jobs and social value to rural areas, preserving valuable and scarce natural resources, reducing GHG emissions, and protecting biodiversity (Noleppa, 2016). This document identifies which research and development activities should be preferentially reinforced in the CSIC to meet the challenges facing Biotechnology and Plant Breeding in the 21st century.

Two scientific breakthroughs in particular, can be considered as game changers and can foster big leaps forward in the development of new plant varieties with improved properties. They act synergistically, endowing researchers with new toolkits to launch ambitious strategies. One is the "omics" revolution; during the last decade, the genomes of many crop species and model plants have been sequenced, and their proteomes and metabolomes have been extensively characterized. The concurrence of all this 'omics' datawith advanced molecular biology and biotechnological tools has enabled an increasingly precise knowledge of the function of plant genes, proteins, metabolites, and their interactions (Scheben et al., 2016). We are living in the era of the "data deluge". The second game changer is the development of increasingly sophisticated New Plant Breeding Techniques (NPBTs), including genome editing, which has developed spectacularly in the last decade (European Commission, 2017), offering new possibilities of redirecting metabolic and developmental processes, or designing new ones, to increase yield, develop tolerance to biotic and abiotic stress, improve food nutritional composition, or transform plants and algae in efficient biofactories for manufacturing added-value products, among other objectives (Brodie et al., 2017). Although 'omic' technologies and NPBTs are already applied by CSIC research groups, a reinforcement of both is needed at the institutional level along with the necessary bioinformatic capacities to successfully face the challenges of agriculture in the 21st century framework of climate change and population growth.

These greatly improved capabilities to access, characterize, and modulate the fine structure of genomes, have to be mobilised to produce improved crops. The ever-increasing information produced needs to be linked to phenotypic information in a multicrop context (Harfouche et al., 2019). To achieve this, the current constraints are in phenotyping (recording the characteristics of plants and algae), prototyping, and data analysis (particularly, bioinformatics), which must be scaled up to keep up with the data flow from basic science and 'omics. The "business as usual" scenario may fall short to respond to these threats, and we must find ways to foster quantum leaps of primary production. According to FAO, by 2050 the world's population will reach 9.1 billion, 34 per cent higher than today. Population growth imposes great pressure on primary production to feed an increasing number of inhabitants without increasing the cultivated area.

On the other hand, the adoption of technological solutions by the public is a sensitive issue. The negative perception of Plant Biotechnology inherited from the past now threatens to delay or even impede the use of NPBTs which, like gene editing, are key for the development of future crops. A large proportion of the citizens mistrust the mixing of science and food. Therefore, next to the scientific and technological objectives, Biotechnology and Plant Breeding faces the challenge of improving the communication of the advantages of science-driven approaches (Malyska et al., 2016). This effort is necessary to disseminate that biotechnological tools, and evidence-based scientific decisions in general are safe and essential for the general well-being.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

2.1. Current context situation

The classic objectives that have traditionally directed research in the area of Plant Breeding over the past century and the first two decades of this century, are still valid today: the study of the organisms responsible for primary production and to develop deeper knowledge to develop new vvarieties. These objectives, however, need renovation in response to a changing environment, co-evolving pests and diseases, population growth, and the needs of producers and economic sectors involved. At the same time, the population is changing in its structure and consumption habits, demanding products not only of higher quality but also personalized nutrition adapted to the specific requirements of certain groups such as athletes, pregnant women or those suffering from intolerances and/or allergies (Derossi et al., 2020). Climate change is already impacting food production in the world, and clearly so in Spain. The scientific consensus indicates that its effect will inevitably increase during this century, with rising temperatures, reduction of water available, increased CO_2, and in more frequent episodes of drought, flooding, or salinization in many world areas including Spain (Trnka et al., 2011). Furthermore, it is expected that the intensity of some pests and diseases will increase and crops will have to face new threats. Plant varieties need to be adapted to these dramatic climate changes. In consequence, the current food production systems will not be capable to respond to the demands, due to shortages of land, freshwater, and suitable climates to continue with business as usual scenario. In Europe, Spain holds some of the most diverse and complete sets of germplasm of arable crops such as cereals and legumes, horticultural and fruit crops, which can be mined for breeding purposes. These local varieties are well adapted to our climatic conditions and, in many cases, have not been systematically exploited in plant breeding. The large diversity of Spanish climates ensures that, for centuries, crops have been adapting under conditions that prefigure those that will be encountered in the future in other regions of Spain, and in Europe. Local germplasm is an invaluable tool for Biotechnology and Plant Breeding in the climate change era.

The fight against climate change happens not only by adapting to it and mitigating its consequences but also by promoting alternative production systems for non-food products such as biomaterials, fine chemicals or medicines, with a lower carbon footprint, within the context of the so-called “bioeconomy”.

Green bioproduction also favors alternative agriculture models such as "vertical farming", which allows decoupling primary production from land use, and promote the development of new crops or new uses of existing ones. However, the development of economically viable bioproduction systems requires the undertaking of ambitious breeding programs that are more comprehensive than those traditionally implemented, and which will often be directed towards the acquisition of new and unconventional traits. Thus, next to maximizing yields of added-value endogenous or recombinant products, the new desirable traits would require the full redesigning of the crop, including growth habits, incorporation of new signalling pathways, or adaptation to the growth conditions of biofactories.

In the local context, agriculture faces serious problems of competitiveness, which is contributing to the progressive abandonment of cultivated land and depopulation in rural areas. Biotechnology and Plant Breeding may contribute to developing new crop varieties and products (annual, forest, perennial, horticultural, algae, etc.), by boosting the untapped local genetic variability and applying scientific knowledge to raise the value of local agricultural products. Moreover, increased competitiveness of food products will also come from quality diversification, targeting diverse groups of population, and from healthy and more nutritious products for safety and health-concerned consumers.

In this scenario, producing more with less, with higher quality, and being sustainable, under increasingly demanding environmental conditions, is a phenomenal challenge that we, as a society, need to tackle to ensure food security.

2.2. Exploring the challenge at international and global levels

There are a number of active communities at the national and international level which have taken positions on this challenge. These communities have defined research and development challenges, some of them in the form of position papers.

The Food and Agricultural Organization (FAO) defines five strategic objectives for sustainable development which are relevant to this challenge, namely ensuring Food Security, increasing Agriculture Sustainability, reduction of Rural Poverty, enabling Efficiency and Inclusivity and increasing Resilience to threats and crisis. The recent report "The Future of Food and Agriculture" (FAO, 2017) analyzes the Trends and Challenges of Agriculture in the 21st century and identifies a number of associated challenges. Relevant to Biotechnology and Plant Breeding is the need to "sustainably improve agricultural productivity to meet increasing demand" (Challenge 1), indicating that "investments in agriculture, fishery and forestry, and spending on research and development need to be stepped up, particularly in and for low-income countries". Other relevant challenges are "Addressing climate change and intensification of natural hazards" (Challenge 3) and "Making food systems more efficient, inclusive and resilient" (Challenge 6). The Global Plant Council (GPC) a coalition of 30 organizations representing plant, crop, and environmental sciences identifies four main challenges in this area: (i) Knowledge, data and resources promoting the exchange of knowledge, ideas, data, resources, and best practice; (ii) Food and human health: increasing the number of crops produced and consumed, increasing diversity within one type of crop, or traditionally or genetically engineered biofortification of staple crops; (iii) Agricultural productivity and sustainability: to find ways of 'sustainably intensify' food production to meet future demand, without losing valuable habitats and diversity, and not producing more greenhouse gases or water pollution, and at the same time reducing our use of inputs such as nutrients, water, energy, capital, and land; (iv) Adaptation to climate change: to generate crop varieties with increased drought resistance, water use efficiency and increased disease resistance; to promote the use of alternative, orphan, and perennial crops; to preserve crop diversity, and develop better agronomic practices. At a global level, it is worth mentioning DivSeek, a global community-driven Not-for-Profit organization that aims to facilitate the generation, integration, and sharing of data and information related to plant genetic resources.

At the EU level, the "Plants for the Future" European Technology Platform, has produced documents reflecting the view and perspectives of EU plant scientists. In the position paper *"Plant breeding as the cornerstone of a sustainable bio-economy",* European Plant Science Organisation (EPSO) defines the following approaches: (i) Improving resource use efficiency and resource stewardship (nutrients, soil, land, etc.); (ii) Improving yield and securing reliable harvests for increased resilience in dynamic environments (including tolerance to abiotic stress in changing climate); (iii) Improving plant health by tackling prevalent diseases; improving resistance to those pests that have a major impact in Europe; and strengthening efforts to anticipate emerging diseases; (iv) Developing plants with improved composition for animal nutrition; reducing the environmental footprint. A second position paper entitled "*Research and Innovation towards a more sustainable and circular European agriculture"* explores synergies between the livestock and crop sectors. This paper defines the following Research and Innovation policies (relevant to our challenge): (i) Developing bio-refineries for increased European protein and nitrogen self-sufficiency including improvement of methods for plant and manure processing and extraction and use of plant secondary metabolites for animal care; (ii) Improving genetics of agricultural crops for reduced environmental impact and fitness as animal feed. This gives priority to yield improvement and reduced sensitivity to pests of crops including grain legumes, increased protein content and protein bio-availability of the plant protein fraction in the different crops as part of an overall strategy. Also at the EU level, the European Cooperative Programme for Plant Genetic Resources (ECPGR) brings together stakeholders in Europe collaboratively, rationally and effectively conserve *ex-situ* and *in situ* Plant Genetic Resources for Food and Agriculture, to provide access and increase sustainable use.

Outside the EU, at the international level, the UK Plant Sciences Federation defines a number of challenges. Those most relevant to our mission are (i) Challenge 1: Food security. Adapting to climate change and extreme weather. Tackling plant pests and disease; (ii) Challenge 2: Producing healthier foods. Using resources more efficiently. Protecting biodiversity; (iii) Challenge 4: A green bio-economy. Producing bioenergy. Making bioproducts. Other important sources for scientific policies in the agrobiotechnology fields are the Agricultural Research Service U.S. Department of Agriculture and Agriculture and Agri-Food Canada.

At the National level, an important player in the Plant Biotech community is the BIOVEGEN Technology Platform (a public-private entity), whose objective is to improve the competitiveness of the sector through the development of technologies from Plant Biology. To this end, it articulates entities of the Spanish agri-food sector, bringing technology supply and demand into contact, and generating business opportunities through the collaboration between the Academy.

3-KEY CHALLENGING POINTS (KCPS)

3.1. KCP1 - Discovery of genes conferring resilience of plants to climate change.

Predictive Plant Breeding is only possible if we know the function of genes, including their interaction among themselves and with the environment. Therefore, we face the challenge of the *identification of key genes and metabolic pathways for developing productive and high-quality crops in a sustainable framework*.

A number of genes/pathways, associated to enhance quality, yield and resilience to higher temperatures and/or CO_2 air concentration, drought, salinity, and biotic stresses that could be used in as many crop species as possible, should be delivered. Thus, implementation of translational strategies in crops, and primary production in general, should be brought to the forefront of CSIC activities.

What needs to be addressed in this KCP?

1. To establish the yet unknown functions of thousands of plant genes and their underlying regulatory mechanisms in crops using plant model systems, in particular:
   - Identification of genes, structural variation, metabolic pathways, and metabolites conferring resilience to climate change conditions.
   - Unravelling the genes that control plant development and phenological responses, to overcome juvenility in trees and loss of adaptation due to seasonal shifts in annual plants.
   - Deciphering plant-microbe interactions to increase nutrient use efficiency and crop productivity.

2. To understand gene-environment relationships at the molecular and epigenetic levels in crops.
3. To develop and test hypotheses for the action of specific genes, pathways, metabolites of potential agronomic relevance.

3.2. KCP2 - Exploit existing and new genetic variability to develop productive cultivars better adapted to current and future conditions

The driving force of this KCP is to put plant diversity to work for us. Optimal crop production relies on growing the best cultivars adapted to local conditions and population needs. Therefore, we must improve crops for the current conditions and also look for the germplasm, traits and genes needed to maintain the productivity and the quality of the crops of tomorrow. Where will these traits and genes come from? The premise for a successful plant breeding is the existence of genetic variability. Fortunately, Spain is one of the richest European countries in plant genetic resources, adapted to a wide diversity of local climates. Another stream of genetic variation will be the deployment of genes and alleles discovered or created by applying fundamental processes from KCP1.

Plant characterization, the current limiting factor of plant breeding, must be scaled up, in the field (through national trial networks), and in controlled environments (prefiguring future conditions), by systematic high-throughput phenotyping (Yang et al., 2020). Phenotypes then will be linked to genotypes, generating catalogues of traits, genes and plant materials with high added value. Mobilising and translating this knowledge requires building a pipeline for the delivery of promising materials to private and public breeders, bolstering multi-crop pre-breeding activities for Spanish climates. To achieve this, the CSIC should engage the local research and development community by launching and leading the creation of a Spanish public-private partnership for multi-crop germplasm testing and pre-breeding. This strategic action would bridge the gap between public research and the seed and nursery sector and could be facilitated by benchmarking currently ongoing initiatives, in other European countries: Designing Future Wheat, UK; Breedwheat, France; Proweizen, Germany; Nordic Public Private Partnership for Pre-breeding. It will require a multidisciplinary approach, bringing in expertise from genetics, genomics, biochemistry, physiology, biotechnology, bioinformatics, plant protection, and breeding.

What needs to be addressed in this KCP?

1. Deployment and optimization of massive phenotyping techniques for plants and algae.
2. Expansion and enhancement of the exploration of the genetic and phenotypic variability of agricultural species with high-throughput methods under controlled and managed environments, and multi-environment field trials.
3. Bolster pre-breeding activities, exploiting the genetic potential of landraces, wild relative species and new variability created with biotechnological tools.
4. Implement precision breeding strategies to incorporate advances from KCP1.

3.3. KCP3 - Addressing crop quality and food security for a growing population

This *challenge aims to develop crops to produce food and products 'a la carte'*. High-quality food and feed products are in high demand by agriculture and industry. The population increase requires high food production with the lowest environmental impact. Future approaches have to boost not only crop production but also quality, providing added-value crops for producers and diverse and healthy balanced diets that meet consumers' expectations. Quality goes beyond products with a suitable shape and color; they have to respond to the demands of increasingly diverse and demanding consumers. Athletes, pregnant women, vegetarians or those suffering from allergies and intolerances have specific requirements for plant products, adapted to their needs. This is particularly important for elderly or vegetarians for whom plant products can be nutritionally improved. In the case of animal feeding, feed composition has a direct impact on the growth rate and health status of the animal as well as on the animal's product quality and on the environment. NPBTs, including synthetic biology, along with optimized breeding strategies, are key for producing healthier crops and ensuring food security.

What needs to be addressed in this KCP?

1. Go deeper into the knowledge on fruit development and ripening, with special emphasis on its flavour and texture, recovering "old but true flavours" and higher quality varieties
2. Development of new plant varieties to diversify our current diet: Adaptation of new crops, new uses of existing crops or recovering the cultivation of traditional varieties adapted to specific areas.
3. Obtaining of functional plants enriched in beneficial bioactive compounds for health: for example, antioxidants or carcino-static compounds.
4. New plant varieties for specific population groups, for example gluten-free cereals for coeliac disease sufferers, or other improved plant-based products for the elderly, vegetarians or athletes.
5. Development of forage crop varieties of high digestibility and nutritional properties to promote animal welfare and sustainable farming.

3.4. KCP4 - Smarter plants for improved sustainable bioproduction

The goal of this KCP is to turn plants and algae into powerful biofactories for the production of valuable compounds to be used not only in the agrofood sector, but also other industrial sectors such as health and medicine, fine chemistry or renewable energy. Photosynthetic organisms are the most efficient bioproduction systems on Earth. Plants are already used to produce the widest range of biostuffs, from fibres, wood, oils, and sugars. The new breeding and genome editing tools, including synthetic biology, offer us unprecedented possibilities to refactor developmental processes or re-direct metabolic fluxes to increase product yields (Wurtzel et al., 2019). In the context of a sustainable bioeconomy, plants and algae are ideal platforms for manufacturing added-value bioproducts. However, the type of complex breeding required for biofactory design demands the adoption of the so-called iterative *design-build-test* strategies, where new genetic interventions are rapidly implemented and tested, and the outcome of such tests is used to inform the model in a new iteration of the cycle. The development of such iterative discovery pipelines will allow us to fill the gap between basic research and agriculture-scale production, taking the lead in the development of smart green biofactories and fueling the creation of economy-viable plant- and algal-based production lines.

What needs to be addressed in this KCP?

1. Development of optimized plant and algae biofactory chassis, with integrated smart systems able to control gene expression, and improved gene delivery methods such as viral vectors.
2. Establishment of plant and algal systems for bioproduction of complex proteins like antibodies or enzymes.
3. Production of antigens for vaccine development. Rapid expression of proteins in plants and algae will allow to shorten the vaccine production time compared to the traditional route.
4. Plant metabolic engineering for producing complex biochemicals, nutraceuticals or pharmaceutical only found in trace amounts in nature.
5. Production of high-quality biofuels, environmentally friendly agrochemicals, or fertilizers.

3.5. KCP5 - Communication and dissemination

Past experiences with genetically modified organisms (GMO) have shown that technologies cannot be developed in isolation from social, ethical and environmental considerations. Increase awareness of the need for fundamental science, *effective communication of Biotechnology and Plant Breeding gains, and particularly dissemination of NPBTs among the general public, decision-makers, policy-makers, and public/private institutions must be achieved.* The success of this KCP will largely depend on creating synergies between researchers, convincing decision-makers that NPBTs are essential tools to increase agricultural productivity, and thereby the economy, without unacceptable risks to the environment or human and animal health; and also to enable the general public to make informed decisions on the uses of NPBTs, providing them with the information on the benefits, risks and impact. We need to incorporate journalists, recruit influencers and contribute to forming new ones to serve as communication nodes, having the CSIC as the "Spanish scientific brand", especially in social media.

What needs to be addressed in this KCP?

1. To participate in scientific seminars at all education levels (including university) to disseminate the science from the CSIC, highlighting the challenge Biotechnology and Plant Breeding, and particularly to promote acceptance of the plant genome engineering techniques. Contribute to teach scientific thinking early in education.
2. CSIC leadership in scientific activities in cooperation with pre-university schools; the CSIC exists and is the leadership.
3. Presence in the media and social networks to effectively influence stakeholders, decision-makers, and policy-makers.
4. The CSIC should coordinate the development of activities aimed at all audiences.

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ANNEX 1

ANNEX 1. PLANT BREEDING RESEARCH. Publications available until February 2020 at the *Web of Science* database were retrieved by combining the plant species name and breeding keywords as indicated below.

Publications	Total Hits	% CSIC Total	% CSIC Spain
Cereals			
wheat	92,596	0.9	31
rice	62,861	0.5	31
maize	46,879	1.2	43
barley	26,441	1.7	37
rye	16,474	0.4	30
oat	8,740	1.2	38
triticale	2,417	0.7	17
quinoa	955	2.6	51
tritordeum	119	62.2	75
Vegetables			
tomato	32,030	2.4	35
potato	27,453	0.9	34
Brassica	16,703	1.2	42
pepper	8,605	2.0	25
cucumber	8,342	1.5	35
beet	7,920	1.2	31
lettuce	6,428	2.7	41
egg plant	5,125	1.1	33
cabbage	4,894	1.1	46
onion	4,592	0.8	27
carrot	4,426	1.4	30
spinach	3,273	1.7	41
broccoli	2,359	3.0	36
cauliflower	2,267	1.7	44
garlic	2,212	1.2	27
sweet corn	1,917	2.3	71
cucurbita	1,761	1.0	13
turnip	1,198	2.7	50
asparagus	1,130	3.0	38
saffron	709	1.4	11
kale	697	2.9	54
brussels sprouts	320	1.9	67
Legumes			
soybean	37,498	0.6	31
bean	20,009	1.7	39
pea	11,113	2.7	53
peanuts	7,132	0.3	13
chickpea	4,754	2.5	49
lentils	2,216	2.5	47
lupinus	1,657	3.4	52
Nuts			
almond	2,553	9.3	38
walnut	2,013	0.9	15
chestnut	1,932	2.3	20
hazelnut	1,297	0.8	11
pistachio	995	1.1	15
acorn	818	4.5	23

Publications	Total Hits	% CSIC Total	% CSIC Spain
Oil crops			
cotton	22,019	0.5	30
olive	11,913	7.8	30
sunflower	9,884	3.6	41
rape	6,637	0.4	28
mustard	5,148	0.8	40
Fruit			
apple	20,022	1.0	18
orange	14,624	2.2	28
grape	12,889	3.5	28
berries	8,148	2.6	36
strawberry	7,526	2.1	28
peach	6,968	5.8	44
pear	5,482	1.0	16
banana	5,133	0.5	19
cherry	5,004	2.1	25
melon	3,501	6.3	44
mango	3,488	1.0	22
plum	2,790	7.0	47
lemon	2,549	2.8	30
watermelon	2,399	1.5	25
papaya	2,134	1.1	35
apricot	2,029	9.3	61
avocado	1,285	2.4	33
nectarine	1,128	7.4	37
kiwi	454	0.7	13
tangerine	327	1.8	35
cherimoya	105	28.6	57
Forest			
Woody species			
pine	17,774	1.6	22
medicinal plants	10,534	0.2	18
vitis	7,745	4.3	37
eucalyptus	7,099	1.1	15
oak	6,585	3.1	26
poplar	5,079	0.4	14
birch	3,984	0.3	11
Ornamental plants	3,888	2.0	41

• Total hits: number of publications retrieved by searching: TS=(plant species) AND TS=(breeding OR germplasm OR tolerance OR resistance OR quality OR yield). Horizontal bar length is proportional to the value contained in the cell.

• The same search was repeated twice including the address AD=(Spain) or AD=(CSIC). The percentage of publications with CSIC contribution is shown respect the total hits (Total) or respect the Spain publication number (Spain). Cells in the "Total" category were shaded using a 2-color scale to improve values visualization, the cell with lowest value is colored white and cells holding values equal to 20 or above are colored red. Cells in the "Spain" category are colored using the same rule, except that red indicates the cell holding the highest value.

ANNEX 2

ANNEX 2. PLANT BIOTECHNOLOGY RESEARCH. Publications available until February 2020 at the Web of Science database were retrieved by combining the plant or algae species name and biotechnology keywords as indicated below. Also, publications on the use of plant biotechnology tools in bioactive molecules development is shown.

Publications	Total Hits		% CSIC			
			Total		Spain	
	genome editing (GE)	*synthetic biology (SB)*	*GE*	*SB*	*GE*	*SB*
Arabidopsis	1,050	266	1.2	2.3	65.0	66.7
rice	773	61	0.8	0.0	46.2	0.0
maize	297	39	1.3	5.1	44.4	50.0
Marchantia or Ppat	119	12	0.0	0.0	0.0	0.0
microalgae	106	83	0.0	1.2	0.0	100
Nicotiana benthamiana	85	44	3.5	6.8	75.0	100
Medicago	29	15	6.9	0.0	100	0.0
Lotus japonica	14	7	14.3	0.0	100	0.0
Brachypodium	2	1	0.0	0.0	0.0	0.0
nutraceuticals	8	48	0.0	2.1	0.0	33.3
phytoremediation	3	7	0.0	0.0	0.0	0.0
agrochemicals	2	19	0.0	0.0	0.0	0.0
biostimulants	1	1	0.0	0.0	0.0	0.0

• Total hits: (Top table, genome editing column) number of publications retrieved by searching: TS=(species) AND TS=(genome editing OR CRISPR OR TALEN OR ZFN). (Top table, synthetic biology column) number of publications retrieved by searching: TS=(species) AND TS=(synthetic biology). (Bottom table, genome editing column) number of publications retrieved by searching: TS=(category name on the left column) AND TS=(genome editing OR CRISPR OR TALEN OR ZFN). (Bottom table, synthetic biology column) number of publications retrieved by searching: TS=(category name on the left column) AND TS=(synthetic biology). In order to improve data visualization, two value groups were defined: plant species (including GE and SB categories) and bioactive molecules (including GE and SB categories). Horizontal bar length is proportional to the value contained in the cell.
• The same search was repeated twice including the address AD=(Spain) or AD=(CSIC). The percentage of publications with CSIC contribution is shown respect the total hits (Total) or respect the Spain publication number (Spain). Cells in the "Total" category were shaded using a 2-color scale to improve value visualization. The cell with lowest value is colored white and the cell holding the highest value is colored red. The same shading was applied to values in the "Spain" category. Both shadings were done for the top and bottom parts of the table independently.

Lower plants analyzed: *Marchantia polymorpha* (Marchantia) and *Physcomitrella patens* (Pp)
Microalgae analyzed: *Nannochloropsis gaditana, Haematococcus pluvialis, Dunaliella salina, Chlorella vulgaris, Chlorella zofingiensis* and *Chlamydomonas reinhardtii.*

ANNEX 3

ANNEX 3. PLANT BREEDING AND BIOTECHNOLOGY PATENTS. Patents published in the Jan 2000- Feb 2020 period available at the *Espacenet* database.

PATENTS		% CSIC	
	Total Hits	Total	Spain
Technology			
Plant Breeding	34,455	0.01	4.9
Transgenic plants	23,289	0.19	19
Haploid plant	3,263	0.03	0
Plant breeding and mutation	1,635	0.06	100
Genome editing	1,358	0.37	100
RNAi plants	1,238	0.40	42
Breeding-Plant species			
maize	15,068	0.01	29
rice	13,804	0.01	20
wheat	8,761	0.01	20
barley	1,761	0.06	17
Trait breeding			
Crop yield	1,174	0.09	0
Drought tolerance	1,022	0.10	100
Plant disease and Biotechnology	330	0.91	43

• Total hits: number of patents found for each category indicated on the left column. Horizontal bar length is proportional to the value contained in the cell.
• The percentage of patents with CSIC contribution is shown respect the total hits (Total) or respect the Spain patent number (Spain). Cells in the "Total" and "Spain" categories were shaded using a 2-color scale to improve values visualization, the cell holding the lowest and highest values are white and red, respectively.

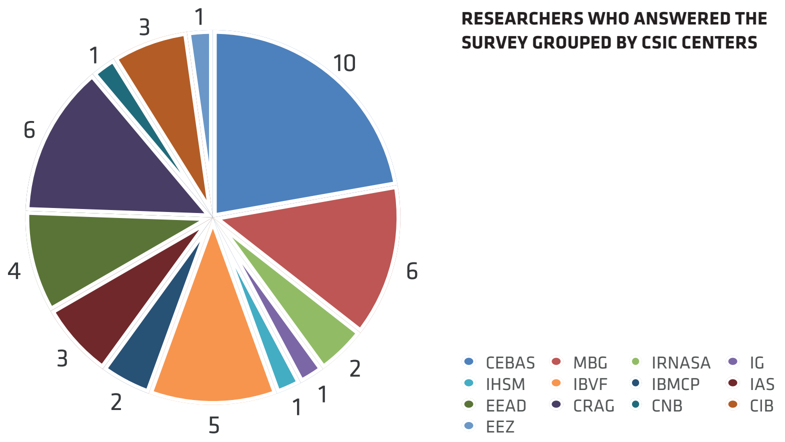
ANNEX 4

ANNEX 4. Summary of the answers to the most important questions of the 'Biotechnology and Plant Breeding challenge' survey (45 responses)

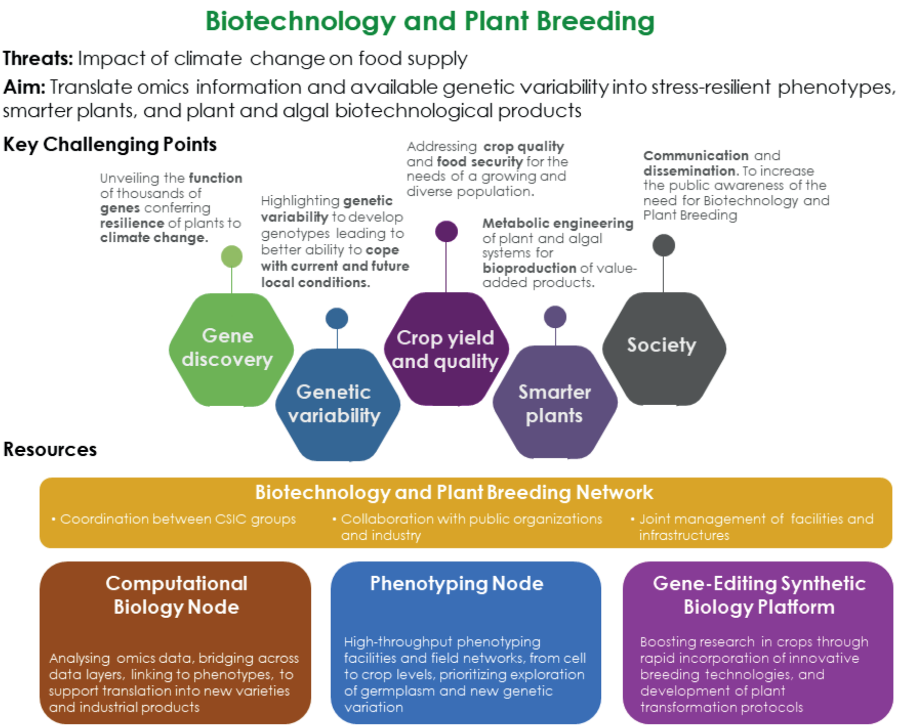
Main scientific problem that should be addressed (from the CSIC point of view)	**Proposal to solve the problem**
Lack of biodiversity of agricultural and forestry systems. *We need variability to increase system sustainability, resilience, profitability and quality in scenery of climate global change and global trade.*	• Use of the genetic potential of breeding and prebreeding material, landraces and wild relative species or create new variability with biothenological tools. Besides, material characterization, from genotype to phenotype, passing through transcriptome, metabolome, and proteome, and know how they respond to different environmental conditions and stresses for an efficient utilization of germplasm in breeding
Breeding has to focus on adaptation of crops to specific and changing environments; tolerance to abiotic stresses as salinity, drought, high CO2, and extreme temperatures; resistance and sustainable crop protection to biotic factors: current and new pest and disease including virus vectors; and good plant development with low inputs. Always minimizing the impact on the environment and maintaining yield and quality. *We need to develop new systems such as: new crops or new uses of current crops, organism different to crops for example microalgae that are essential organisms to eliminate CO2 and cope with global climate change.*	Before breeding: • To create new knowledge about the process involved in plant development, reproductive meristem activity and fruit formation as well as investigate the molecular mechanisms determining yield and quality crop conditions under normal and stress conditions; • The use of an integrated approach combining physiological and biochemical traits along with the transcriptome response may help to the identification of relevant metabolic processes and underlying molecular mechanisms in the response of crops to stress. In addition, it is necessary to study the genetic networks that integrate those gene functions and their relevance to balance productivity and defense against abiotic stress • Study of genetics bases for tolerance and resistance to pests and pathogens and also research on effects of environment-determining parameters (both, of abiotic or biotic nature) on mechanisms and processes that underlie compatible infections of plants and parasite and on the interaction plant-parasite For breeding: • To define selection criteria and genetic designs for setting up efficient breeding programs aiming at releasing improved varieties for a sustainable agriculture. To accomplish that, set up 1) an organized system, at the appropriate scale, to screen local diversity for selection criteria; 2) a pre-breeding pipeline to introduce superior materials found in the first step into elite material, with involvement of private companies-organizations
New plant breeding techniques (breeding methods and biothecnological tools) for developing new varieties for sustainable crop production face to the climate change	• Promote several common infrastructures, projects to promote greater coordination between groups and specialized bioinformatic staff • Application of high throughput technologies to identify the limiting factors of the systems • Adapt biotechnological tools for crops in which they have not yet been developed • Optimization of new breeding methods such as genomic selection • The results of basic research in model plants must be efficiently transferred to crops.

Main scientific problem that should be addressed (from the CSIC point of view)	**Proposal to solve the problem**
Lack of coordination between research groups and with groups of other national and international institutions	• More communication among breeders within CSIC, maybe create a National Group for Crop Breeding and Biotechnology • Large consortium of pathologists, stress physiologists, agronomists, breeders, geneticists, engineers, bioinformatics, private companies. • Information about research has to be shared and managed so research on big data should be implemented • To share experiences on these challenge with a working group (farmer and scientific people) and try to identify opportunities at large scale (finding new crop species or obtained by biotechnology tools and/or breeding), discussing options to address these challenges and enhancing and encouraging cooperation and collaboration among various partners • Potentiate collaborations with research in other countries by funding exchange programs and joint projects. • Contact to companies in order to inform them about current research in this field in Spain
Bureaucratic aspects: lack of infrastructure, funding, PhD students, field and laboratory workers	• Higher financial support

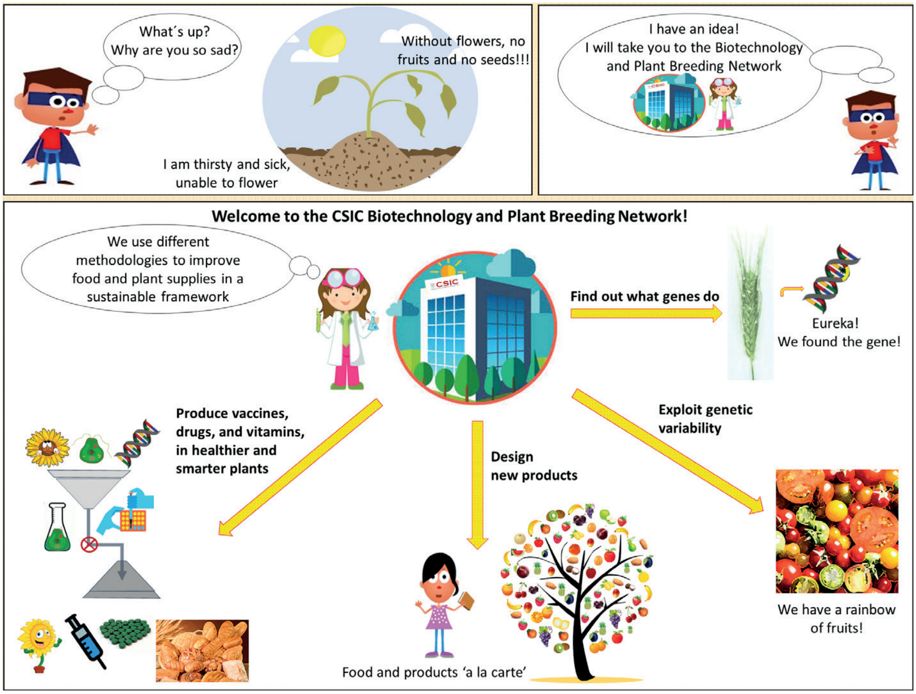
RESEARCHERS WHO ANSWERED THE SURVEY GROUPED BY CSIC CENTERS



SUMMARY FOR EXPERTS



SUMMARY FOR THE GENERAL PUBLIC



CHAPTER 6

ABSTRACT

Challenges in the food industry relate not only to demographic pressure and environment protection, but also to new consumer demands and specific health requirements. Multidisciplinary studies on raw materials, waste valorisation, efficient green technologies, new products and biodegradable smart packaging are needed. Real-time process control, quality, safety and authenticity will rely on powerful proces analytical technology, multi-sensors and advanced computing and digitalisation systems.

KEYWORDS

circular economy | biorefinery
waste valorisation | raw materials
green technologies | functional food
biodegradable packaging | food industry 4.0

CHAPTER 6

SUSTAINABLE PRODUCTION IN THE FOOD INDUSTRY

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EXECUTIVE SUMMARY

Demographic pressure and climate change force the industry towards the use of more sustainable processes to increase productivity and minimize environmental impact. The food industry may find innovative ways to reduce multiple species overexploitation by optimizing raw materials and promoting the use of waste and by-products. Process Intensification following the green chemistry principles is the basis of the Biorefinery concept, aimed at biomass processing into value-added products. Residual biomass can be also used to produce biodegradable and smart packaging systems. Innovative processes based on efficient and eco-friendly technologies represent a key topic for sustainable food production, allowing the reduction of harmful additives at the same time. The food industry should be also prepared to provide innovative products in a fast and reliable, flexible and even customizable way to fulfil new personal health requirements and lifestyles. However, it will be necessary to identify and prevent frauds and emerging risks related to changes towards more sustainable production systems. A rigorous process control using powerful multi-sensors and analytical and computational tools that allow a real time quality and safety control along the different production steps, is of utmost importance. A food industry revolution based on digitalization and automation

is foreseen, by integrating robotics, artificial intelligence and Big Data. This challenge requires new knowledge generation through data collection and analysis covering different areas of the productive system from a holistic perspective based on multi-disciplinary approaches. The following key challenging points should be addressed: (i) diversification of raw materials in connection to innovative solutions within the primary sector; (ii) mechanisms optimization for the rational use of water and wastes following Process Intensification and Biorefinery models; (iii) innovative strategies based on more efficient technologies, natural additives, microorganisms and new molecular markers; (iv) innovation in food products development towards personalised consumers' health by integrating multidisciplinary databases and designing robust in vitro evaluation models and clinical trials; (v) complex databases and mathematical models to ensure food quality, safety, authenticity and traceability, based on powerful process analytical technology and multisensors combined with advanced computing and digitalisation; (vi) development of resistant biodegradable packaging from industrial waste, capable to offer real-time information by including smart systems for predictive labelling, traceability and digitalization.

1. INTRODUCTION AND GENERAL DESCRIPTION

The main challenge for the food industry is to produce and provide food supplies for an increasing world population. According to FAO, by 2050 the world will have more than 9000 million inhabitants. Two out of every 9 of them will be older than 60 and most will live in urban areas. The ever increasing demand for foods is intensifying the pressure on multiple aquatic and terrestrial species which may lead to serious consequences on biodiversity and ecosystems stability. Such an imbalance may be worsened by the introduction of foreign species. Seas overexploitation, for instance, has led to the enforcement of the new European regulation on the common fisheries policies (Regulation (EU) No 1380/2013). Unwanted catches are discarded and cannot be employed for human consumption; however, an appropriate transformation could represent a viable alternative to use those resources. The food industry may find innovative ways to integrate the conservation of biodiversity with the sustainability of the production by means of diversifying the origin of the raw materials, adapting the existing processes to other alternative underused or invasive species, as well as fostering the use and valorisation of wastes and by-products for the development of new products. This approach is even more important in geographical areas characterized by extreme poverty, drought, or lack of natural resources, where the exploitation of ancestral crops and autochthonous animal species, both with enhanced resistance to plagues and diseases can be encouraged. Multiple "exotic" species and varieties that may be rich in nutrients and bioactive components would also represent a new source for different flavours and textures. Furthermore, the valorisation of insects and halophyte plants would be also a sustainable option. It would be advisable to foresee the new scenarii that will arise due to climate change to adapt the marine and terrestrial food production to, most probably, more demanding conditions. Both demographic pressure and the evolution of climate change will direct the food industry towards the enhancement of process sustainability as a rational means to increase production and minimize the environmental impact simultaneously. The action plan adopted by all UN Member States in 2015, as part of the 2030 Agenda for Sustainable Development proposes a complete transformation of the food industry from economic, societal and environmental perspectives. Water consumption reduction and appropriate wastes and effluent management and valorisation to be re-used in the production processes, are factors of utmost importance contained in the actions defined by the different international organizations to foster "zero wastes" approaches and the transition to Circular Economy. This model is also related to the concept of Green Chemistry, which through its 12 principles, considers that the design and improvement of products, materials, and processes ensuring environmental protection is achievable (Anastas and Warner, 2000). The design of innovative processes introducing more efficient technologies, assisted by biotechnology and nanotechnology, represents a key topic for sustainable development in the field of Industrial Ecodesign. The concept of Process Intensification, initially related to the chemical industry, was implemented with the aim to maximize the energy efficiency of physicochemical processes with the minimum environmental and economic costs. This efficiency enhancement may be possible in terms of increased yields or reduced processing time or energetic consumption, and seeks the selection of the optimum processing conditions including greener and safer technologies-based innovative strategies. The processes may be integrated into a sequential approach (including different unit operations as, extraction, reaction, drying, among others) for the attainment of the targeted product. Process intensification and integration are the foundations for the new concept of Biorefinery. A biorefinery is defined as the processing of raw biomass into diverse value-added commercial products (foods and ingredients, feed, materials, chemical products and specialties, fertilizers, etc.) and/or energy (heat, fuels). In order to properly assess process sustainability, quantifying how all the parameters involved comply with the green chemistry principles is essential. In this regards, a relevant aspect of industrial Ecodesign deals with the implementation of tools for environmental management. Among the different available tools, Life Cycle Analysis (LCA) is one of the most interesting to assess the environmental impact of a process or a product through its life cycle (processing of raw materials, manufacturing, distribution, use, recycling, and final disposal). LCA allows the quantification of both resource consumption and environmental emissions.

On the other hand, the food industry should be governed by safety and quality standards, not only established by the applicable regulation but also by the industry and by the market and consumers' requirements. Those standards are defined by physicochemical, microbiological, nutritional and sensory food properties and also by other factors that are explicitly (e.g., labelling information) or implicitly (e.g., own consumers' expectations) related. It is necessary to control the different stages within the Food Value Chain through the application of the concept "Food Integrity". Food Integrity implies that a given food not compliant with the required standards will lose its integrity harming the production sustainability. Thanks to the implementation of advanced traceability systems and procedures based on the development, validation, standardization and application of new strategies, including the latest technical developments and the comprehensive characterization of food products, the needs of different stakeholders can be met (from primary production and environmental aspects to consumer needs). In this regard, process control in the production chain is critical to provide a fast evaluation of the raw materials, the process intermediates, and final products, avoiding losses due to low quality, shelf-life or eventual health risks.

Access to a healthy and sustainable diet is a key life requisite. The relationship between food, nutrition, and health, which is very complex, dynamic and multifaceted, is strongly influenced by biological, environmental, societal, cultural and behavioural factors. Surprisingly, whereas around 800 million people suffer from chronic undernourishment worldwide, the incidence of obesity and diet-related diseases (cardiovascular diseases, diabetes type 2, cancer, osteoarthritis, among others) are increasing in the so-called emerging and developed countries. In these latter countries, the population pyramid is reversing due to a decrease in birth rate and an increase in life expectancy. Therefore, besides ensuring sustainable production of food to fight malnutrition, it is also essential to consider those societal changes that will surely lead to an increased demand for foods enriched on specific nutrients or natural bioactive compounds, that is, functional foods. New personal needs and lifestyles will increase the demand for healthier fast food, organic, vegan or allergen-free products, among others. The boom experienced by social networks and information technologies will contribute to increasing the demand for higher quality and diversity of food products, and for more detailed information regarding food origin, traceability, authenticity, composition and nutritional properties with a stronger commitment to environmental protection. Thus, the food industry should be prepared to design and provide innovative products in a fast and reliable, flexible and even customizable way. Moreover, it will be necessary to identify and prevent frauds and emerging risks related to changes in production systems due to the exploitation of new raw materials, to the reuse of wastes and by-products, to the manufacture of minimally processed products, as well as those related to the reduction of additives due to new regulations or the boost of organic products. To face these new trends and needs, a revolution on the industry is foreseen, going towards the implementation of the Industry 4.0 based on digitalization and automation integrating robotics, artificial intelligence and collaborative robots (Cobots), Big Data or even Internet of Things (IoT) (Miranda et al., 2019).

Lastly although also important, the food industry shall assume the responsibility to use biodegradable packaging helping to reduce the environmental impact. Strategies to significantly reduce the use of single-use plastic materials, especially, light plastic bags (<50 μm thickness) that should be replaced by 100% biodegradable materials (Regulation EU 2015/720) are already enforced. At this point, residual biomasses and effluents, as well as wastes and underused raw materials might play a key role in the generation of those new packaging materials. Besides providing proper resistance and protection, novel and innovative food packaging should be suitable for the integration of smart sensors that will help to guarantee appropriate quality and safety control along the whole food chain.

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

2.1. Green Chemistry and Process Intensification

The food industry has to face the challenge of increasing energy efficiency and using renewable energy, as well as reducing water requirements and greenhouse effect gases emission. Water, residual biomass and effluent reuse through Process Intensification is an essential step for sustainability because it fosters the transition towards Circular Economy beyond just recycling. In this regard, the Green Chemistry principles should be applied as one of the main aims to protect the environment. The boost on biorefinery models to obtain added-value bioproducts implies not only a comprehensive previous knowledge of the use of biomass but also of the processes to be applied (Lau, 2016). Advanced green extraction techniques, such as supercritical fluids, ultrasounds, microwaves, nanofiltration, pulsed electric fields, etc., are already successfully applied for the recovery of bioactive compounds from plants, seaweeds, microalgae, and food-related by-products. Besides organic solvents recycling, novel more environmentally-friendly solvents are being tested, such as natural deep eutectic solvents (NaDES) that are non-volatile, non-flammable substances from renewable sources that are safer than traditional organic solvents. Although the transition to the Circular Economy is recognized as a chief need for sustainable development, the main difficulty is related to the lack of integrative knowledge. Multiple partial studies of circular systems and green extraction technologies are already available. Moreover, the composition and potential of some materials have been extensively reported, as well as the potential use of decontaminated effluents. However, these are generally incomplete studies without a holistic perspective, with no industrial application or not enough technological innovation.

2.2. Technological innovation

Another possibility for sustainable development is based on the implementation of more efficient innovative processing technologies avoiding the use of chemical additives. There is an increasing interest in non-thermal methods for food processing, including pulsed electric fields, pulsed light, hydrostatic ultra-high pressures, irradiation, hydrodynamic pressure, high power ultrasounds, radiofrequency, UV radiation, cold plasma, among others, to achieve inactivation of microorganisms and to extend food shelf-life. These technologies offer enhanced energy efficiency compared to traditional processing since they are operated at low temperatures and short processing times with low or no environmental emissions. Moreover, the food nutritional value is not affected, thus making possible the manufacturing of additive-free minimally processed products, which can be categorised as "clean label". Some of these technologies, as for instance pressure-assisted heat treatments, are promising to produce foods with long shel-life for space missions, combat rations or emergencies. However, their industrial development has to be further studied. The maintenance of the sensory quality attributes without affecting some labile foods, such as fish, is still a challenge. Combined treatments with bioactive natural compounds or extracts, or with edible coatings, are a possibility to avoid unwanted effects, although more complex developments are required. In the field of restructured products more efficient technologies than conventional thermal processing are available, such as thermal extrusion, ohmic heating, microwaves heating, high pressure, etc. These can be useful for process optimization and also to obtain new texture or appearance. The optimization of process parameters and the combination of novel technologies are also key factors to improve energy efficiency, yield and/or final product quality in drying and dehydration processes, pasteurisation, sterilization, and freezing of foods and ingredients. In this connection, wastes and by-products are similarly prone to spoilage and, thus, fast and efficient stabilization is needed. In particular, although dehydration is interesting to reduce the volume and facilitate handling, transport, and storage, it may reduce their biological or functional potential. Freeze drying would be an exception; however it is time-consuming and entails a high investment cost in industrial equipment and energy expense. An example of novel technology gaining interest exponentially in food innovation is 3D printing that retains a good potential to "print" foods and ingredients partially or totally customised in terms of format, structure, texture, flavour, nutritional value and specific formulations (Otcu et al., 2019). This technology, which is still immature at a methodological level, has a primary goal for prototypes generation, digital production at a small scale, or even in the so-called "molecular gastronomy" that is based on the application of scientific concepts to cooking.

2.3. Biotechnology

The use of biological systems and living organisms or their metabolites is an option to improve process sustainability as well as to create or modify food products. Biotechnological processes such as composting, anaerobic digestions and biogas generation, or bioethanol production, among others, are already established for the sustainable management of wastes generated within the food industry. The main challenges associated with this field are related to the integration of processes under Circular Economy as well as to their engineering development. For instance, the use of microbial strains with fewer requirements in food and beverage fermentation processes is a means to contribute to saving energy and water consumption from the heat/cooling systems. Moreover, sensory quality and uniqueness of traditional fermented foods could be improved by fostering microbial biodiversity in those fermentation processes avoiding the use of commercial strains and starters that may lead to standardised and highly similar products. This could be even more important in developing countries in which autochthonous fermented products constitute a relevant part of the diet for those less favoured. In terms of quality and food safety, the reduction of additives with harmful health effects, such as sulfites in winemaking or crustacean derived products, is an objective for the industry within its commitment to sustainability. In this regard, biopreservation, explained as the use of yeast and bacteria (or their metabolites) with protective activity against pathogens and other spoilage microorganisms, is an area with high scientific interest to improve food quality and food safety and to extend products' shelf-life. Another aspect with increasing importance is the use of living organisms (microorganisms, cells, marine or terrestrial invertebrates, holobiont or associated species, etc.) as high-performance cell factories for the production of tissues and molecules with biological or technological activity (peptides, enzymes, polyphenols, etc.) or to produce metabolic biotransformation of compounds into more active molecules. *In vitro* meat production is an example of a potential future product that still requires great research efforts, apart from other ethical, safety and regulatory issues. Biotechnology is also present in the development of foods and diets directed towards health maintenance and disease prevention through the production of probiotics, prebiotics, psychobiotics and other bioactive compounds with beneficial effects on human microbiota (mainly, oral and gut microbiota) and microbiota-related diseases.

2.4. Nanotechnology

The impact of nanotechnology in sustainable food production is high in very diverse fields, such as nanosensors and nanogauges development, pathogen control, membrane technology, adsorbent materials or controlled release of active compounds. Unique optic and electric properties of nanomaterials, their high surface–area–to–volume ratio, and the possibility to have functionalized surfaces might facilitate the detection of pathogens or specific chemical compounds in food samples with higher accuracy and sensibility than traditional sensors. Besides, this detection can be performed on reduced sample volumes thanks to miniaturization and lab-on-a-chip analytical platforms. However, their behaviour when applied to complex food systems has to be confirmed. Metallic nanoparticles or water nanodrops with hydroxyl radicals produced by electrospraying are examples of applications that have demonstrated promising antimicrobial activity in the field of pathogen control although their mechanisms have to be still clarified. Indeed, the toxicity of metallic ions vs. nanoparticles should be elucidated. Possible interferences of environmental and food matrix related factors on antimicrobial activity have to be also understood. Many developments have been carried out in food packaging materials (polymeric materials with improved properties, active packaging, nanomaterials and even intelligent packaging with nanosensors) and in contact surfaces, specifically, superhydrophobic nanostructures that avoid the formation of bacterial biofilms. Nanotechnology is also useful to optimize water management and effluent treatment to recover compounds of interest, thanks to the production of membranes or nanostructured adsorbent materials that allows improving efficiency, permselectivity or sorption capability by paramagnetic materials. The introduction of magnetic nanoparticles in adsorbents, for instance, allows easy separation of water by generating magnetic fields. The behaviour of these systems in the presence of complex biomass or high concentration in organic matter is still unknown. Besides, efficiency and yield should be improved to justify the implementation of this approach at the industrial level, due to its high cost. Other advantages of nanotechnology are the functionalization to improve the selectivity of solutes, the specific photocatalytic reactions or the transformation of substances. Techniques such as nanoemulsion or nanoencapsulation are currently being explored in food-related applications for the development of functional foods, improving the bioavailability of the bioactive compounds. They are also applied in agronomy for the controlled release of fertilizers and agrochemical compounds avoiding their degradation or volatilization. Translocation of nanoparticles in plants has been reported, although their assimilation mechanisms remain unknown. The application of pesticides into nanoparticles has demonstrated an increase in their efficiency and a lower requirement of solvents in the formulations. However, there is a lack of validation studies under real conditions (salinity, pH, organic matter or antimicrobial activity).

2.5. Quality and process control

Research targeted to both prevention and detection is required for better food quality and safety control. For that purpose, all changes that take place during production, processing and distribution, the effect of biological and climatic variables and the interaction of the food with the consumer before and after ingestion (perception, healthy effects, etc.), should be considered. The analytical methods employed nowadays for process, quality and safety control normally involve the use of conventional instruments. At times, more advanced instrumentation is also used, requiring long analysis times and costly equipment. The implementation of concepts such as Process Analytical Technology (PAT) and Quality by Design (QbD), firstly introduced by the pharmaceutical industry, might be a useful model also for the food industry (Van den Berg, 2013). These are based on the use of powerful detection and analytical tools combined with databases and predictive mathematical models that allow a real time quality and safety control along with the different production steps. “Horizon scanning” is just another example of a methodology based on predictive and proactive control systems able to foresee quality and safety issues, thanks to data modelling obtained from different sources (composition data, climatic, economic, etc.). The highest difficulty to implement these methodologies is related to the huge biological, chemical and structural complexity involved in food systems. For this reason, robust and fast analytical platforms, able to handle a great amount of data and to auto-learn overcoming the limitations of the technologies used at present, are required. Multisensors, -omics technologies, bioinformatics, and chemometric tools for data handling and/or neuromorphic network systems, as well as process modelling and events prediction, could be important assets. Sensors based on fluorescence, NIR, FTIR, NMR, Raman, microwaves, and ultrasounds are becoming more affordable and combined with chemometric tools, they allow a wide sampling and real-time determination of the composition, structure, oxidation, authenticity, etc., during processing. However, there is still a long way to go from research to its real-life productive application. On the other hand, sensory quality analysis requires trained panels, involving a great amount of time and resources. Moreover, it is characterised by other shortcomings such as discrepancies due to human factors and not allowing online assessment. Multisensor systems combined with chemometric tools and pattern recognition, known as electronic noses and/or tongues, are well suited for this purpose (Escuder-Gilabert and Peris, 2010). These systems allow classification and discrimination, simultaneous qualitative analysis of multiple components and quantitative analysis, even mimicking the sense of taste. Specific areas in which multisensors applications are more extended are food quality control and safety assessment. In fact, two available commercial instruments are currently working as electronic tongues (α-Astree, AlphaMOS, France; TS-5000Z, Intelligent Sensor Technology, Japan). Chemometrics represents a key tool to get proper results from electronic tongues. By modelling the underlying relationships and structure between the different properties measured in the system, the cross-sensitivity of multi-sensor systems can be used to calibrate their response to interference due to matrix effects. These models can be also used to predict complex biochemical parameters and to classify samples (e.g., identification of critical outbreaks of biological or allergen contamination). The current state-of-the-art is based on offline analysis, using trained models with static responses from the sensors matrix. To facilitate pattern recognition, input data are generally transformed into a smaller dimensional space by linear and non-linear algorithms and support vectors machines (SVM) (Granato, 2018). Deep neural networks (DNN) (Zhang, 2017) provide multilayer scalable representations to adapt to the complexity of the studied issue using biochemical information continuously acquired. The integration of applications, as well as the data storage, processing and analysis in the cloud, may facilitate the high computational cost required. As the number of sensors increases and the information is stored along time, raw data transference through the internet becomes a bottleneck slowing down the chemometrics analyses. The need to alleviate this problem has originated a rise in edge computing systems where information is pre-processed *in-situ* by algorithms in embedded computers with limited resources. This imposes the need for a truly efficient design, optimized in algorithmic, architectural and circuitry terms (Verhelst, 2017).

'Omic' technologies that are based on high throughput analytical tools (mass spectrometry, DNA and RNA sequencing, microarrays, NMR, etc) have been already applied to diverse food industry-related studies, including food quality and food safety, authenticity, traceability, as well as human nutrition and systems biology (Sebedio and Malpuech-Brugere, 2016). Foodomics, genomics, proteomics, lipidomics, and metabolomics are powerful tools for species identification and to prevent typical food frauds (dairy, meat or fish products, for instance). They are also useful for the detection of transgenic organisms, contaminants, and degradation products arising from food processing and storage. For instance, RNA sequencing and high sensibility metabolomics may be used to study the molecular mechanisms of fruit and vegetable spoilage during post-harvesting storage. DNA sequencing technologies are employed in aquaculture and agronomy for the description and regulation of biochemical routes, biomarker identification as well as to study the epigenetic regulation of fruit ripening, among other applications. Epigenetics can be also very relevant in the study of food bioactive compounds. Metabolomics has important branches in human nutritional epidemiology for the identification of biomarkers relating health and diet, or biomarkers of metabolic diseases. The obtained information is highly relevant to the development of functional foods. However, the need to study the detection of frauds and emerging risks associated to the development of new products (sustainable-processed and functional foods, food supplements, etc.), market globalization, etc., has evidenced the current limitations on the availability of markers to ensure origin and authenticity, that could be able to overcome the ever-increasingly sophisticated food frauds related to food quality and safety. In this regard, the development of non-targeted, multi analytical, and -omics approaches will contribute to the exhaustive characterization of those products. From this point, new markers for the fast, sensitive and selective detection of frauds and risks derived from their consumption could be established. Lastly, the evolution and development of data science will probably play a key role allowing the analysis of the great variety of food matrices, frequently very complex, and the interpretation of the analytical information collected. This is an aspect that could be improved in the future, together with the application of robust methodologies for routine analysis in the industry.

2.6. Valorisation and functional foods

The chemical, structural, and functional characterization of the multiple interesting compounds present in residues, by-products, water effluents, wastes or even alternative species, has attracted a lot of research interest in the last decades due to the high potential for the generation of added-value products and new food products. Food wastes and by-products represent a natural source of biopolymers with diverse techno-functional capabilities. For instance, cheese whey proteins, meat and fish discarded muscle proteins or even animal blood proteins may be used for manufacturing products or as technological ingredient (gel-forming, emulsifier, foaming, flavouring, etc.) in the form of protein hydrolysates. Collagen from skins, bones, or scales, and chitin from crustaceans or cephalopods' pens are a source of gelatin, glycosaminoglycans and chitosan; wastes and by-products from vegetal products are rich in starch, cellulose, hemicellulose, pectins and lignin. Besides their use in food products, biopolymers and their more active hydrolysed fractions (peptides, oligosaccharides) are also explored to produce hydrogels, microcapsules, and nanoparticles in pharmaceutical, regenerative medicine, tissue engineering or cosmetic applications.

Nowadays, the use of non-toxic natural crosslinking agents (phosphorylated compounds, phenolic compounds, aldehydes, salts, sugars, etc.) is one of the main strategies to increase their functionality. Multiple examples of bioactive compounds with potential to be used in functional foods already exist. Lactoferrin and prebiotic oligosaccharides from dairy products or different mammalian hormones are well known examples. However, vegetal residues are probably the most studied due to their diversity and high content on bioactive compounds (polyphenols, carotenoids, tocopherols, vitamins, minerals, glucosinolates, proteins, phospholipids, etc.) able to exert physiological effects. The search for alternative protein and fat sources to those of animal origin using vegetables to produce similar foods, not only in terms of appearance but also at a sensory level is an ever-increasing worldwide trend because they might be healthier as well as more environmentally respectful and sustainable. Fish viscera, algae, and microalgae are good sources for omega-3, in particular, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), as well as for antioxidants including tocopherols and carotenoids. Recently, the interest in the recovery of marine phospholipids as sources of omega-3 has increased, due to their relative oxidative stability by synergies with tocopherol or by changes in their structure in the presence of water. These latter changes are responsible for the general ability of phospholipids for the development of liposome encapsulation systems. Considering that liposomes are included in the Regulation (EU) 2015/2283 on novel foods, their use as bioactive ingredients in functional foods is an area with high potential. Apart from technological development and valorisation of by-products, the functional food industry has to be prepared to provide solutions for individual or group diet patterns, for specific nutritional requirements to improve health, and for contributing to reduce the risk of non-transmittable diseases through the diet. For that, deeper knowledge is needed, for instance, regarding the interaction between nutrition and exercise or cognitive functions as well as the potential of nutrients/bioactive components to regulate energy homeostasis, transcriptional processes, molecular routes or the microbiome. In particular, the modulation of the microbiome might be useful for preventing pathogen infections or as a therapeutic strategy against dysbiosis-related diseases. There are numerous studies dealing with the biological activity, bioaccessibility and bioavailability of natural compounds; however, interdisciplinary approaches are required to integrate biological, physiological, societal and economic factors that will allow the development of customised foods directed to improve health and/or reduce the incidence and risk of non-transmittable diseases. Likewise, the relationships diet-genetics-epigenetics in terms of personalised nutrition is a huge challenge to which the functional foods industry may provide answers.

2.7. Biodegradable packaging

Nowadays, bioplastics are an alternative for biodegradable packaging beyond the use of paper. Bioplastics generated from biological materials, such as polylactic acid (from maize or sugarcane) or polyhydroxyalkanoate (PHA) (from microorganisms) have received criticisms due to their high production costs as well as for spending natural resources that could be used for food instead. Besides, for their total biodegradation, they have to be submitted to composting processes (requiring special treatment conditions and temperatures higher than 60 ºC). For these reasons, some experts have introduced the term *greenwashing* to refer to products that may deceive consumers regarding their sustainability. Thus, the use of food industry-related wastes and by-products to generate new packaging materials is an increasingly preferred option. Biodegradable biopolymers from renewable sources are receiving attention as they are perceived as more environmentally respectful, even more, if they are produced using green extraction and purification procedures. Besides their food-related use, these can be also employed in agronomy-related applications for crop protection, contributinge to soil enrichment during their biodegradation. A lot of efforts have been focused on the increase of functionalities as a part of the packaging, as an antioxidant and/or antimicrobial coating, as controlled release systems for bioactive compounds, or as matrices for the integration of chemical indicators and intelligent sensors for quality and shelf-life control. However, significant research development is still needed to have natural biodegradable biopolymers replacing conventional plastics for food protection against mechanical damage and external contamination or able to resist the application of new processing technologies, labelling, integration of smart sensors, IoT devices, geolocation, etc. The formation of box- or tray-like rigid structures produced by thermo-pressing of simple or composite biopolymer matrices is another alternative requiring further development. Those structures may include coarse reinforcement particles from animal (feathers, hoofs, nails, shells) or vegetal (bagasse, fruit shells, etc) wastes with minimum processing and without requiring exhaustive purification.

2.8. Interaction between primary production and the industry

Besides the interest in the exploitation of alternative species for the protection of biodiversity, the interaction between primary production and the food industry has a great influence on sustainability. For instance, it is important to link animal wellbeing and nutrition in animal farming and aquaculture with genetic profiles that allow optimum meat, milk and fish production and quality. It is also relevant to precisely know the post-harvest fruit and vegetable responses to stresses in agriculture due to climatic change (high temperatures, drought, radiation, etc.). The loss of 10% of cultivable ecosystems due to erosion, climatic change or salinity is foreseen. Therefore, it will be necessary to ensure a higher production in smaller spaces with lower water consumption. Hydroponic farming or "soil-free agriculture" and aeroponics, also known as vertical farms, which consist in replacing soil by mineral solutions or hydrogels and natural light by artificial light, could be considered as future sustainable production alternatives. These growing systems could help to reduce water consumption by 90%, although their big-scale application is still not feasible. Power consumption should be reduced to that aim. On the other hand, regarding the sustainable production of healthier fats, a good alternative would be the development of seeds and oil-rich fruits with higher content of non-harmful long-chain saturated fatty acids (e.g. stearic acid) or rich in oleic acid and/or omega-6 and omega-3 polyunsaturated fatty acids; for instance, cocoa fats, olive oil or high-oleic seeds oil as well as fish-like oils (the latter have been already obtained experimentally from genetically modified seeds). Improvement and selection of oleaginous crops is the most sustainable and viable alternative to (i) animal fats, especially from bovine and ovine origin, that are rich in unhealthy saturated fatty acids and require a big quantity of resources for their production, (ii) partially hydrogenated vegetable oils, enriched on *trans* fatty acids, even more harmful than saturated fatty acids, and (iii) vegetable fats rich in palmitic and lauric acids, with important detrimental implications on blood LDL cholesterol levels and cardiovascular diseases.

3. KEY CHALLENGING POINTS (KCPS)

This challenge requires the generation of new knowledge through data collection and analysis covering several different areas of the productive system, including industrial scale-up, and from a holistic perspective based on multi-disciplinary approaches. Moreover, energy and production efficiency, environmental sustainability and impact on society should be considered as a whole. The key points that should be addressed in the future within the present challenge are described below:

3.1. To increase food production through diversification and optimization of conventional and new raw materials for consumption or industrial processing.

This point involves the identification and adaptation of terrestrial and aquatic alternative species to face overexploitation avoiding any health risks. New innovative solutions applied to the primary sector to increase productivity should be warranted, anticipating the deleterious effects of global warming and climate change. These solutions include (i) a functional genomics approach for the identification of molecular markers and their use in genetic programs (mutagenesis, transgenesis, or gene editing) for crops and farm animals; (ii) domestication of animal and vegetable species, both from terrestrial and aquatic origin (including seaweeds and microalgae), for their intensive growth and adaptation to the effects imposed by climate change; (iii) increased knowledge of biochemical mechanisms and optimization of growing conditions (agronomy, animal wellbeing, and targeted feeding); (iv) development and validation of nanomaterials for the controlled release of agrochemicals with activity against environmental stimuli; (v) implementation of digitalization tools, robotics, and nanotechnology for the real-time control of productive parameters and potential associated risks.

3.2. Fulfilment with the model of Circular Economy through the optimization of mechanisms for the rational and efficient use of water and wastes, and the improvement on the quantification of the environmental impact by an update on the reference values.

This key point considers: (i) optimization of circular recycling, drying, and waste and effluent reuse systems; (ii) identification, characterization and stabilisation of residues with an integrative perspective according to the particular production process and geographical location; (iii) biomass reuse following Biorefinery and Process Intensification models by applying the concepts of Green Chemistry and the use of biotechnology, nanotechnology, and enhanced physical separation technologies; these include the use of new green, safe, and selective solvents that could be directly employed in food applications, as well as innovative membranes; (iv) innovative functionalisation of waste and residues through the development of advanced materials for food, pharmaceutical or biomedical use, natural ingredients and additives, biofuels or fertilisers.

3.3. To establish innovative food processing and preservation strategies avoiding the use of additives and reducing the risk of biotic and abiotic contaminants, without hampering both organoleptic and nutritional quality.

This point considers: (i) optimization of non-thermal processing technologies, more efficient thermal treatments, drying and dehydration, freezing, sterilisation, extraction and refining, as well as personalised production at a local scale; (ii) development of multifunctional natural additives and systems involving microorganisms with bioprotective activity; (iii) pathogen control using surface-functionalised metallic and biopolymer nanoparticles; (iv) valorisation of the microorganisms collections for the improvement of biotechnological processes; (v) identification of molecular markers linked to the impact of new technologies on composition, safety, and food shelf-life by multi-analytical techniques and by multi-omics approaches.

3.4. To promote innovation in industrial products to introduce new (or significantly improved) products to the market capable of meeting the increasingly strict and diverse demands from society.

This point considers: (i) technological and biotechnological development of new products, ingredients, and multi-functional foods, preferably from underused natural resources, wastes and by-products; (ii) verification of the absence of toxicity and risk of bioaccumulation of new compounds and ingredients, with a special interest in the area of nanoparticles; (iii) design and integration of multidisciplinary databases from genetic, phenotypic, physiologic, societal and economic analyses that allow the development of personalised foods directed towards consumers' health improvement; (iv) design of new *in vitro* models for the evaluation of the biological activity, e.g., based on stem cells for organoids production and their application to evaluating the effect of bioactive compounds in health; (v) development of individualised foods based on the particular microbiome to foster the growth of specific species useful to prevent chronic diseases in which the microbiome may exert a significant effect; (vi) design of more robust, reproducible and standardised clinical trials that allow the validation of the effect of new foods as a base for personalised nutrition, gaining insight on nutrigenetic, nutrigenomic and epigenetic aspects; (vii) generation of new bioconversion processes to produce new functional foods; (viii) establishment of a regulatory legal frame and improvement on communication policies to foster functional foods consumption.

3.5. To implement new models based on PAT tools and QbD allowing process design, monitoring, and control as well as inline quality and critical control point assessment, along with the integrated reporting of environmental analysis, to guarantee proper food quality, safety, authenticity, and traceability.

This point considers: (i) characterization at molecular, biochemical and structural level of raw materials and ingredients, so that integrated information in complex databases allow the construction of reliable mathematical models to predict the properties and shelf-life of foods, and also facilitate the industrial scale-up; (ii) optimization of analytical platforms for the detection and the in-line analysis, based on powerful and integrated methodologies and the design of multi-sensors, multi-analyte nano sensors and neuromorphic systems of high sensibility and specificity; (iii) identification of new markers for the fast detection of frauds and emerging risks; (iv) application of basic knowledge to the development of digitalisation systems, advanced computing, Big Data, robotics, artificial intelligence, and IoT.

3.6. To eradicate contaminant plastics spreading to the biosphere through the regular use of completely biodegradable packaging systems with resistance and functional properties similar to those of conventional plastics.

This point considers: (i) design of complex biodegradable materials with high resistance obtained from microorganisms or compounds from industrial wastes and by-products, reinforced with minerals, natural crosslinking agents, nanostructures and/or physical treatment; (ii) adaptation of those materials to conventional and emerging technologies for industrial processing; (iii) development of active and smart packaging based on the use of bioactive compounds and natural indicators; (iv) advanced systems for predictive labelling, traceability and digitalization with IoT capacity (microchips, sensors, transductors, etc.) capable to offer real-time information in the food label regarding the food chemical composition and expiry date.

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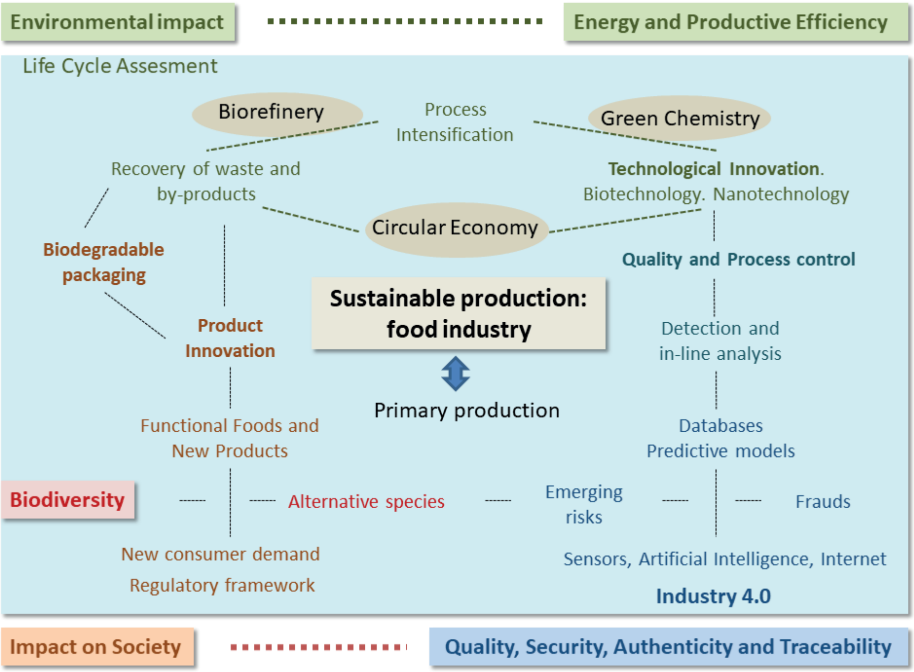
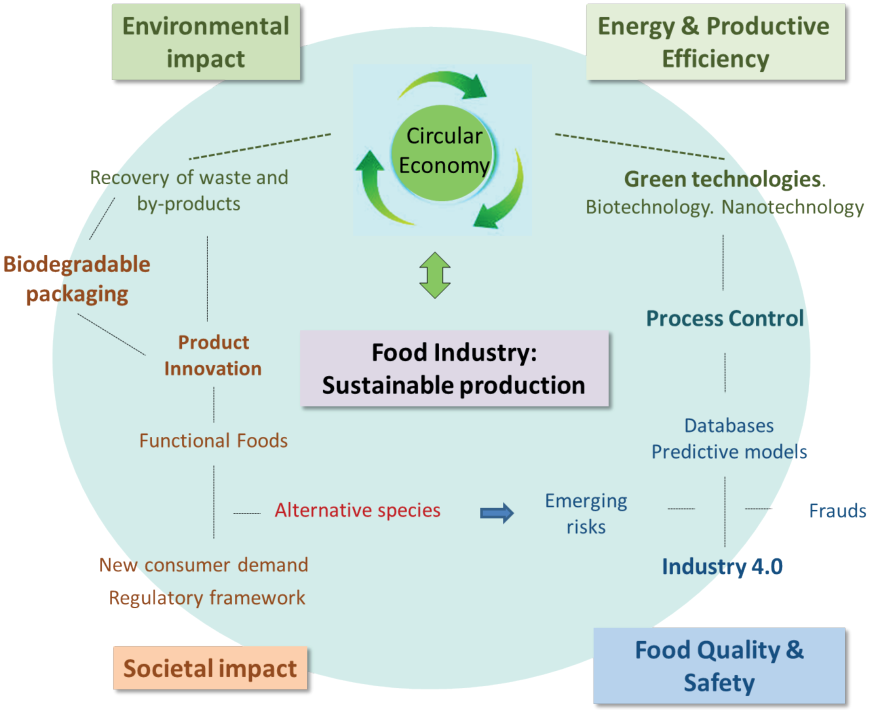
SUMMARY FOR EXPERTS



SUMMARY FOR THE GENERAL PUBLIC



CHAPTER 7

ABSTRACT

Emerging and re-emerging food safety risks are driven by climate change and other factors like globalization, water scarcity, population aging, and migration, among others. These factors affect the persistence and occurrence of conventional and emerging primary risks. Successful initiatives to manage emerging risks need to identify, evaluate, and prioritize potential risks as well as to respond with sustainable strategies able to reduce the threats.

KEYWORDS

emerging risks | one health | analytical methods | risk assessment | renewable sources

CHAPTER 7

FOOD SAFETY

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EXECUTIVE SUMMARY

Food safety has a key role in the current COVID-19 pandemic caused by SARS-CoV-2. The most likely ecological reservoirs for SARS-CoV-2 are bats, and it is highly probable that the virus jumped the species barrier to humans through consumption of raw or undercooked animal products. This pandemic emphasized the importance of the one health approach and how crucial aspects related to food safety in the primary production are, and the impact of fresh meat consumption. World food production uses 70% of water resources, emits 25-35% of greenhouse gases, and uses 40% of available land, being its role essential in future sustainability. The United Nations Sustainable Development Goals highlight the need for sustainable food systems by assessing the safety and efficacy of innovation in the food chain. Currently, water availability and accessibility are the most significant constraining factors for the production of crops, livestock, and fisheries, as well as for processing and preparation of these foods and products. Addressing these issues is indispensable for areas affected by water scarcity because water scarcity will be exacerbated by the rapid growth of urban areas, climate change, and bio-energy demands. On the other hand, the world markets for pesticides and veterinary drugs are multi-million euro businesses whose practices are regulated by current legislation due to their direct influence on the safety of treated animals, the farmers who apply the products, the food marketed and the consumers´ safety. Current legislation protects consumers from inappropriate practices by developing

extensive monitoring programs that, in addition to applied chemicals, include the routine analysis of many other persistent, highly toxic microcontaminants distributed worldwide. The current globalization of the food market is promoting, particularly in developed countries, growing pressure from governments and consumers to increase the number of compounds and matrices included in these already complex and expensive monitoring programs. There is also growing concern regarding the potential presence of unknown chemicals or the combination of multiple chemicals in food. Similar considerations are applicable for foodborne pathogens, toxins, or allergens. From a practical point of view, accomplishing such demands will only be possible through the development of advanced (bio)analytical methodologies allowing higher sample throughput while keeping the quality standards set in current legislations and decreasing reagents, cost, time, and energy consumption, and waste generation per analysis. In this context, the development of novel, miniaturized and generic (bio)analytical approaches based on state-of-the-art analytical instrumentation and the identification of new biomarkers for implementation in sensors will represent key achievements ensuring food safety and humans protection.

1. INTRODUCTION AND GENERAL DESCRIPTION

Food safety is concerned to the prevention and control of hazards associated with the consumption of food. In fact, the globalization of food markets in the 21st century creates new challenges for food safety (Fung et al., 2018). These impacts affect the persistence and occurrence of conventional and emerging primary food hazards as viruses, bacteria, parasites, allergens, harmful algae, fungi, toxic contaminants, among others, and the patterns of their corresponding foodborne diseases (WHO, 2015). The European Food Safety Authority (EFSA) recognized the existing high risk throughout the world and identified the need for developing new methods of food safety and control in primary foods. To guarantee consumer safety, a number of regulations in terms of food safety have been implemented (i.e. Regulation (EU) No 1169/2011). As a consequence of these regulations and recommendations, accurate, sensitive, and fast detection methods for food risk control and to guarantee the security to the consumers are highly recommended. In addition to the need for new and optimized detection methods for food risk control, sustainability is the other big challenge faced by primary production. Agricultural production of the future needs to produce healthy and nutritious food in such a way that the ecosystem functions and biodiversity are maintained while dealing with the significant challenges of a growing population, climate change, and declining natural resources. Sustainable primary production can be achieved by the development and implementation of new production technologies that allow more efficient use of natural resources, including land and agricultural inputs (Lewandowski et al., 2017).

2. IMPACT IN BASIC SCIENCE PANORAMA AND POTENTIAL APPLICATIONS

We are facing some major challenges, as described below, that will need to be tackled in the coming years.

- Emerging and re-emerging food safety threats. Some examples are:
    1. Unknown pathogens newly identified, and/or established pathogens appearing in unexpected foods or acquiring further virulence factors;
    2. Antibiotic resistant and multiple-antibiotic resistant foodborne bacteria;
    3. New food allergies and intolerances derived from the introduction of novel foods and from the search for novel sources of protein;

4. Novel chemicals, (bio)toxins, and/or micro/nanoplastics. There is a need to increase the knowledge on the environmental fate and ecotoxicological or toxicological data on these compounds.

Therefore, novel, accurate, and sensitive (bio)analytical and toxicological methodologies are needed to monitor and characterize these emerging food safety threats in a great variety of complex matrices. Additionally, intervention strategies aiming to reduce the prevalence of these emerging risks should be implemented considering global sustainability.

- Food in the circular biobased economy to provide enough nutritious and safe food for a growing and older population. In this context, new and more environmentally friendly and renewable sources should be identified and efficiently utilized.
- Generation of new food systems less vulnerable to global warming.

3-KEY CHALLENGING POINTS

3.1. Impact of climate change and human activities in food safety

3.1.1. Persistence and occurrence of pathogens

Climate change has a high impact on food safety. Remarkably, changes in temperature and rainfall patterns could trigger changes in the survival and transmission of pathogenic bacteria, viruses, and parasites, and thus give rise to the emergence of microbial hazards that would increase contamination of water and food that could be transferred along the food chain to the consumer (WHO, 2018; Cavicchioli et al., 2019). Wheather changes related to climate change can directly affect seasonal enteric foodborne pathogens like *Salmonella* spp. and *Campylobacter* spp., which predominate in summer months and viral pathogens like norovirus and rotavirus, that predominate in wintertime. Predicted increases in temperatures associated with climate change could imply an increase in the multiplication rate of waterborne and foodborne microorganisms (WHO, 2018).

Rainfall patterns have been positively related to runoff of waterborne and foodborne pathogens (Semenza et al., 2012; Cann et al., 2013). Although changes in rainfall patterns and the increase in temperature can be considered the principal weather drivers associated with climate change, other events like floods, heat-waves and droughts may also threaten food safety (Pachauri and Meyer, 2007). In a longer term scenario, expected increase in world growth population would amplify climate change effects (Cavicchioli et al., 2019). Systematic studies have been conducted to investigate the impact of climate change on water diseases. However, the methodological approaches used have been questioned by several authors due to the existence of colllinearity and key factors (biological mechanisms, human behavior) that have not been considered. So, the authors conclude that further systematic studies or tools that permit to separate the effects of weather from others need to be carried out (Lo Iacono et al., 2017). This is why there is a need for quantitative modeling approaches with scenario analyses and additional laboratory experiments.

Water is probably the principal vehicle for those changes associated to climate change to affect humans in terms of food safety. Drinking water and the use of water in agriculture and food systems are the major pathways through which an increase in the contamination of water by climate change can affects individuals. Feces from domestic animals, wildlife, and fields, are considered important sources of zoonotic pathogens for humans by water recreation or drinking-water consumption (Ferguson et al., 2003). Also, along the food chain contaminated water used for irrigation (vegetables), food processing and retailers can cause food outbreaks (Nichols et al., 2018). Among foods, shellfish, as they filter large volumes of water, are commonly associated with foodborne outbreaks with pathogenic microorganisms, like human norovirus and several species of Vibrio sp. An increase in the incidence of non choleorea Vibrios, mainly *Vibrio chloreae*, *Vibrio parahaemolyticus* and *Vibrio vulnificus*, have has been correlated with increasing global temperature or a decrease in salinity of aquatic environments as a result of increased precipitation (Vezzulli et al., 2016, García-Urtaza et al., 2018). Improvement in surveillance of these pathogens, considered as microbiol barometers of climate change, is necessary in Europe, where there is not a continuous monitoring of these emerging pathogens (Baker-Austin et al., 2017).

3.1.2. Anthropogenic organic pollutants and heavy metals

Different types of anthropogenic pollutants can affect the safety of the food chain since they can be introduced at different stages of the food chain/production. Regarding primary production, three main classes can be identified: pesticides, veterinary drugs, and other industrial xenobiotics. The two first families of compounds are intentionally used to control pests and animal diseases during primary production. Nevertheless, fraudulent practices, including, e.g., those orientated to reduce fumigation costs by using phase-out products or to promote an illegal weight enhancement in meat-producing animals, are also repetitively detected and, in consequence, should be routinely controlled to preserve human health. In addition, some of the metabolites and degradation products of these chemicals still remain unknown, and the same consideration applies to their potential toxicity and fate. In the coming years, it is expected that a number of more environmentally friendly, easily degradable and less toxic generation of pesticides will be developed and commercialized. Again, the assessment of the potential impact of these exogenous chemicals and heavy metals on the food chain and their final fate and potential risk for humans when detected in primary production goods will be mandatory.

On the other hand, persistent organic pollutants (POPs) are introduced in the food chain as a non-intentional result of many human activities followed by aerial transport and deposition. POPs also reach plant and animal products as a consequence of not-fully understood/regulated agricultural practices (e.g., application of wastewater sludge containing resistant toxic compounds or unknown transformation products). Besides, primary production goods can be affected by fortuitous processes, such as industrial spills or accidental fires, which can be a source of legacy recalcitrant compounds, including polyaromatic hydrocarbons (PAHs), polychlorobiphenyls (PCBs) and polychloro dibenzo-*p*-dioxins and furans (PCDD/Fs). The inherent toxicity of many of these families of xenobiotics made that current legislations established strict maximum residual levels (MRLs) allowed in food and feed in order to guaranty the safety of these goods and minimize potential human impacts. Latest trends in this field demonstrate that these limits must be constantly re-visited and reduced, at the time that new goods and chemicals (associated either to novel agricultural and veterinarian practices or to new consumers' habits and demands) are incorporated to these legislations to ensure the safety of the food chain. These changes are generally promoted by new knowledge allowing (i) a more accurate estimation of the toxicity of these xenobiotics, (ii) the identification of novel transformation products or chemicals introduced in the environment and reaching the food chain, (iii) a better understanding of the fate of these xenobiotics, and/or (iv) a more accurate estimation of the risk.

3.1.3. Mycotoxins and phycotoxins

Fungal and algal growth and formation of mycotoxins and phycotoxins will lead to changes in occurrence patterns. Mycotoxins are produced by certain fungi (moulds) on crops and can cause both acute toxic effects and chronic health problems (including cancer) in humans and livestock.

3.1.4. Antimicrobial resistance

In the field of food safety, scientists and risk assessors are focused on the evaluation of the factors which may lead to the presence of antimicrobial resistant bacteria in food and animals, and the association between the antimicrobial resistance (AMR) with climate has gained increased attention. Recently, a study has explored the role of climate (temperature) and additional factors on the distribution of antibiotic resistance across the United States, showing that increasing local temperature, as well as population density, are associated with increasing antibiotic resistance (percent resistant) in common pathogens (Macfadden et al., 2018). This study also revealed that the associations between temperature and antibiotic resistance were consistent across most classes of antibiotics and pathogens and may be strengthening over time, indicating that current predictions of the burden of antibiotic resistance could be significantly underestimated in the face of a growing population and climate change (Macfadden et al., 2018). Therefore, future studies are necessary to establish the relationship between AMR and climate change and its impact on food safety.

Antibiotic resistance is a major concern for current and future society because it threatens the effective treatment of infectious diseases. Actually, some bacterial strains acquire antibiotic resistance by recombination of foreign DNA into the chromosome or by horizontal gene acquisition. Several mobile genetic elements (MGEs) have been reported to mobilize different types of resistance genes. Bacteriophages and phage-related particles have been highlighted as MGEs that transfer antibiotic resistance (Brown-Jaque et al., 2015). The extent of the gene movement might be huge as bacteriophages are the most abundant entities in most of the environments. In addition, many phages are able to infect bacteria belonging to different taxa, which increases the chance for gene transfer between different species. Metagenomic studies confirm that bacteriophage particles present in most environments contain antibiotic resistance genes. On the other hand, this transduction would be very important in horizontal transfer from environmental to human body-associated biomes. In this scenario, it is expected that the increase in globalization of future society brings together a higher risk for resistance transmission, making necessary new strategies for controlling it.

Multiple studies have confirmed the beneficial effects of probiotic-bacteria use in the health of both livestock and humans and their consumption is gaining popularity worldwide. However, concerns have been raised in the use of some probiotics strains that carry antibiotic resistance genes themselves, as they have the potential to pass the antibiotic resistance genes to pathogenic bacteria through horizontal gene transfer. It is imperative to implement proper regulations on their use to effectively mitigate their potential contribution.

In most of the countries, surveillance systems only routinely monitor the incidence and antibiotic resistance of pathogenic or indicator bacteria species such as *Escherichia coli* in food of animal origin. There is a growing evidence of fresh produce as a relevant vehicle for the transmission of foodborne illness. However, surveillance of fruits and vegetables is very limited and prevalence data is scarce. Also, evaluation of potential risk factors such as organic manure used as fertilizers and irrigation water should be monitored to obtain reliable data.

3.1.5. Increased exposure to micro(nano)materials

Continuous daily contact with plastics allows oral, dermal and inhalation exposure to chemical components, leading to the widespread presence in the human body of chemicals associated with plastics (Revel et al., 2018; Rist et al. 2018; Vianello et al. 2019). Microplastics (pieces < 5 μm in size) and nanoplastics (< 100 nm) have generated intense public concern due to their persistent nature, their ability to adsorb persistent chemical pollutants, and, therefore, their potential negative impacts on humans and the environment. Contamination of plastics is made mainly in oceans but is extended to rivers and lakes and lately, to soils. They can be ingested by a wide range of aquatic organisms, both marine, and freshwater, and thus have the potential to accumulate through the food chain (Donohoe et al., 2018). There is strong evidence showing that chemical contaminants can bioaccumulate in marine life (e.g. zooplankton, bivalves, fishes, etc.) (Remy et al., 2015) when micro(nano)plastics is ingested. There are different works proving the transfer by ingestion for marine predators of these micro(nano)plastics (Nelms et al., 2018). However, whether these plastic contaminants biomagnify in higher trophic level animals (humans) as a direct result of ingestion still need to be studied.

There is evidence of these particles in salt, honey, sugar, beer, and bottled water (Karami et al., 2017; Rist et al., 2018). However, controversy exists in other studies indicating that there is no contamination or questioning the results (Muhlschlegel et al., 2017; Ossmann et al., 2019). Another study on manufactured food, i.e. canned sardines, indicates that there was a low level of microplastics and with the absence of toxic compounds on them, not posing a health risk (Karami et al., 2018). In summary, we have to be aware that synthetic materials are everywhere in our everyday lives. Not only food can be contaminated but also the exposure to plastic materials, i.e. as food contact materials, can be a risk for our health. Definitely, more research in polymeric materials, standardization, legislation, specifically in nanoscience-nanotechnology, waste management, and recyclability, must be performed to analyze the impact in primary production and the whole food chain.

3.1.6. Impact of human migration in food safety

The movement of people, as recently rise in COVID-19 pandemic, is likely to be the single thing with the greatest impact on European health, and also food safety in the coming decade(s). It will be important to elaborate an overview of the potential threats on food safety that can be expected from vast human migration into Europe; such a list will include people coming with their own infections (some of which may not be endemic in Europe, so will be a diagnostic challenge), the stress on sanitation and hygiene due to the influx of people (keeping food "clean"), the introduction of food habits that may not be suited to European conditions regarding food safety, etc. This challenge will bring together expertise from medical, food production and environmental settings as well as social and environmental factors.

3.1.7. The entry of new pathogens through the movement of vectors

Climate change can promote changes in vector-borne diseases transmitted through ticks, mosquitoes, rodents, and emerging tropical and subtropical species (WHO, 2017). In this respect, although known diseases transmitted by vectors like dengue, Rift Valley Fever, West Nile virus, Zika virus, are zoonosis non-transmitted by foods, international surveillance is required to raise people awareness.

3.2. Emerging and re-emerging risks

3.2.1. Safety of microorganisms used in the food and feed chain

Microorganisms are increasingly used in the food and feed chain as probiotic, pesticide (biological agents), production organisms (with increasing opportunities because of genetic modification and synthetic microbiology), and as biomass (as an alternative protein source). EFSA has to evaluate the safety of the microorganisms at strain level related to the different areas of use and the BIOHAZ panel is responsible for the evaluation of microorganisms as safe (the Qualified Presumption of Safety, the QPS concept). However, microorganisms (even the so-called 'safe' micro-organisms) can cause human infections e.g. in immunocompromised people (increasingly represented in our population) and many non-QPS microorganisms are harboring genes coding for toxins, secondary metabolites with unknown function as well as antibiotic resistance genes as previously mentioned. To improve the risk assessment in this topic, increased fundamental scientific knowledge is needed, requiring multidisciplinary research.

3.2.2. Genetically modified organisms (GMOs)

The provision of alternative proteins obtained from genetic engineering approaches and/or novel food sources is a priority for the innovative EU Research Food 2030 (Food 2030, 2019). In consequence, plants with enhanced resistance to abiotic stress and pathogen infections are needed to support the reductions in greenhouse gas emissions from the food system, as well as to ensure sustainable diets. In this context, new plant breeding technologies, such as genome editing using site-directed nucleases (e.g., CRISPR-Cas system), will enable new gene-edited crops to be developed with greater precision and scope than genetically modified plants obtained by conventional transgenesis. These advances could help farmers and researchers to create a food system less vulnerable to a changing climate (for instance, by developing new crop varieties more resilient to drought) and contribute to sustainability and global food security (Hundleby & Harwood, 2019).

3.2.3. New ingredients and foods

Sustainability and ethics from consumers are increasingly driving food purchasing decisions. In this context, novel foods can represent a suitable alternative to traditional farming and conventional (and unsustainable) foodstuffs. Within this framework, new food applications based on secondary products, including food wastes and by-products, and insects are expected to increasingly reach the market in the coming years. From a practical point of view, insects are preferred over large land animals because their rearing consumes less land and water, and their greenhouse emissions are remarkably lower (Garino et al., 2019).

The consumption of some of these novel food products could pose the following risks:

i. Chemical. Bioaccumulation of heavy metals and/or other chemical compounds such as POPs, presence of naturally toxigenic compounds or antinutrients for humans, etc.

ii. Microbiological. High microbial load, pathogenic bacteria, survival of spore-forming bacteria following processing, mycotoxin-producing fungi, parasites, virus, antimicrobial resistance genes.
iii. Allergenicity. Novel food proteins can represent a hazard for certain subpopulations by triggering allergic reactions in sensitized individuals.
iv. New phytosanitary products and replacement of drugs with alternative substances

The ability of agriculture to continually provide food to a growing world population is of crucial importance. Bacterial diseases of plants have continually reduced production but biocides and other drugs used previously to mitigate these losses should be reduced or eliminated with the consequent threat for future agriculture. Bacteriophages are proposed as antimicrobial agents in agriculture, which could significantly reduce the environmental impact of drugs in the environment and increase profitability by lowering crop loss (Svircev et al., 2018).

3.3. Implementation of an integrated risk assessment approach and tools

3.3.1. Implementation of an integrated risk assessment approach based on the One Health Concept

In recent years the benefits of taking a One Health concept to address public health challenges such as chemical and biological hazards have become increasingly apparent. The lack of integration among different sectors including social and environmental factors limits the understanding of the influence of different factors in the protection and dissemination of risks through the agri-food chain or clinical settings. Using the One Health model, this challenge will bring together expertise from medical, food production and environmental settings to increase our understanding of biological and chemical contaminant relevance, particularly in multispecies and multi-chemicals studies. It will be very important to develop a consensus approach to carry out and validate effective mitigation strategies. Knowledge from social research will help identify right timing and adequate methods of engaging with society during the risk assessment process.

Food safety assessment should rely on studies at the cutting edge of science, which implies continuous updates and, therefore, the development of new methodological tools relevant for food risk assessment (Fernández et al., 2019). Nevertheless, given the complexity of the food supply chain involving from primary agricultural products to total intake by individuals, as well as the diversity and nature of foods, it is unrealistic to provide state-of-art considerations to cover all possible scenarios. Nevertheless, some particular aspects could be foreseen and key bullet points are considered below.

3.3.2. New tools for efficient and integrated risk assessment: big data (integration of genomics, transcriptomics, proteomics, and metabolomic and artificial intelligence)

Genomics and immunoassays techniques have been for a long time the selected methods for food risk detection. Several polyclonal and monoclonal antibodies have been developed enabling a quick and relatively sensitive detection and quantitation method for specific food risks. However, recent studies proved that different immunoassays may suffer from a limited reproducibility, besides of cross-reactivity problems with other matrix components, altered immunoaffinity of epitopes from particular foods, and the lack of multiplexing capability (Díaz-Amigo et al., 2013). On the other hand, DNA-based detection and quantitation methods for food risk control have been developed (Böhme et al., 2019). However, these methods only detect the DNA molecule and not the food risks components (i.e. pathogens, toxins, proteins, xenobiotics), resulting in inaccurate results, especially in the case of low amount of available DNA and in the case of food practices that can alter the DNA molecules. Therefore, the development of alternative and direct fast methods that present high reproducibility, sensitivity, and specificity is necessary.

Proteomics and Mass Spectrometry methods:

Proteomics and mass spectrometry (MS) methods can provide new alternative tools for a confident detection and quantitation of food risks in primary food samples. Bottom-up targeted proteomics scanning methods have been applied to detect and quantify in the foods the presence of several food allergens (Carrera et al., 2018) and to authenticate the species present in the samples (Gallardo et al., 2013). Therefore, the use of reliable and sensitive MS-based proteomics approaches, for both discovery and monitoring of food risks, will enhance the safety of the consumers.

Biosensor devices:

Biosensor devices have acquired a great significance during the last years in a wide variety of industrial primary sectors (i.e. agriculture, food industry), because they are highly sensitive, selective, and accurate detection methods. A biosensor is an analytical device that incorporates two basic elements: a bio-recognition element (i.e. antibody, enzyme, aptamer) used for detection of a specific analyte and a transducer, capable of interpreting this recognition and provide a qualitative/quantitative signal. The advantage of using biosensors instead of other methods consists especially in the possibility to miniaturize the device and perform a real-time in-situ analysis. In addition, traditional lab-based detection methods require trained personnel, scientific knowledge, and often expensive equipment. Linking rapid lab-based biosensors with a smartphone readout system, they become more user accessible. These devices will make possible for the food industry companies and food control authorities to perform the raw material routine risks control test in their own facilities without the need for expensive instrumentations and/or qualified staff.

3.3.3. Novel strategies to reduce food safety risks

The growing human population is currently facing an unprecedented challenge regarding global food sustainability. Thus, it is of paramount importance to maintain food production and quality while avoiding a negative impact on climate change and the environment at large. Along the food chain, several practices, such as the uncontrolled release of antimicrobials to the environment, could compromise future human health. Research has to be focused on exploiting natural antimicrobials with the goal of achieving a safer and more sustainable food production chain. In this context, bacteriophages may become good allies to prevent and treat diseases in farm animals or be used as disinfectants in farms, while reducing the environmental impact of food production (Carvalho et al., 2017).

Scientific advances and the evolution of risk assessment tools should be used to re-design food safety assessment strategies. For example, in the case of the safety assessment of proteins, there is room for improvement due to the basic principles and methodologies currently applied have been previously developed for assessing chemicals (i.e., small molecules), whilst proteins are much more complex biological molecules that could require particular hazards and risk considerations. This fact partly explains that the application of *in silico* methods in risk assessment of toxicity and immunogenicity of food proteins still remains as an ongoing challenge. Therefore, improved *in silico* analysis approaches based on more advanced bioinformatics tools that might better predict the risk of a novel protein to trigger toxic or allergic reactions are expected to be developed in the coming years. Likewise, a refinement of the currently available toxin and allergen databases could also be needed to streamline the safety assessment of food proteins. Additionally, targeted *in vitro* testing tools should be further developed and validated in robustness and reliability to integrate and possibly replace animal models. Animal models can be used to obtain decisive evidence on protein safety only when the initial protein and exposure assessment is not sufficient to conclude on the safety (Fernandez Dumont et al., 2018). Accurate *in vivo* animal models are useful in protein allergenicity and immunotoxicity assessment but none of the approaches have been validated in this context. In addition, these tests are often performed in rodent models, and the importance to develop validated and standardized animal models for the assessment of allergenicity in farm animals has been underlined.

3.3.4. Integration of metagenomics and metatranscriptomics in food safety

Emerging and rapidly progressing omics and genetic technologies will likely have a considerable impact in the future and it is expected that they may provide a high quantity of data and information, even in a systematic way. This scenario opens a completely new perspective that is aimed to generate new knowledge, for instance by using artificial intelligence or sophisticated data mining builder (Parenti et al., 2019). However, the management, data collection, processing, interpretation, storage and curation of such big data require specific infrastructures and bioinformatic pipelines, representing nowadays a great challenge (D'Argenio, 2018) that should be resolved in the future before omics technologies can be routinely used in risk assessment (EFSA, 2018).

Recent evidence has pointed out that using an integration of different omics technologies (metagenomics, metatranscriptomics, metaproteomics, and metabolomics) combined with bioinformatics and advanced computational tools are key factors in the understanding of relevant genes, variants, pathways or metabolic functions characterizing the food products and to monitor critical points in the food production/manipulation chain and the processes in the food industry (Perrotta et al., 2017). Indeed, some expected outcomes may have an invaluable impact on food safety, in order to reduce the risk associated with foodborne pathogens and chemicals, but also to better control spoilage processes (Cocolin et al., 2018). In the field of food allergy, genome-wide association studies (GWASs) may be a powerful tool to identify genes related to IgE-mediated food allergy, including epigenetic mediation (Hong et al., 2015; Marenholz et al., 2017). This information could be crucial to unraveling the pathogenesis of certain IgE-mediated reactions and, therefore, also highly valuable for the allergenic risk assessment of novel proteins.

3.4. Development of advanced (bio)monitoring tools for improved exposure assessment

3.4.1. Development of new analytical strategies for multi-residual and environmental sustainable monitoring of toxic chemicals and pathogens

Current social pressure for food safety, combined with the improved knowledge of the nature, toxicity, and fate of toxic substances affecting primary production, is promoting a constant reformulation of current legislations to ensure a proper control of risk and human potential. Adopted actions include the systematic lowering of the MRLs set for the different commodities, regular incorporation of new analytes to be routinely controlled, constant increase of the minimum number of samples to be analyzed of a given product to ensure the representativeness of the analysis and of the types of samples to be controlled. In practice, this evolving scenario represents an enormous challenge for official and routine laboratories on change of food monitoring programs and demands the adaptation of the analytical methodologies in use to fulfill current demands regarding sensitivity, sample throughput, and rapidness of data treatment and decision-making tools.

Increasing demands in this context made mandatory the development and validation of novel (bio)analytical methodologies able to fulfill previously identified needs for rapid and highly accurate determinations at extremely low concentration levels in an enormous variety of complex matrices. Thereby, new multi-analyte procedures should replace analyte-specific methodologies still in use in many application fields. Miniaturization of the sample treatment procedures should become a key concept when developing novel analytical approaches promoting the integration of the several treatment steps and reducing the analytical time, sample manipulation, and the analyst exposition to harmful reagents and solvents. Miniaturization of the sample treatment is also the first required step when setting-up more automated and, when possible, hyphenated analytical instruments for complete on-line sample analysis. Although these approaches should effectively contribute to reduce the amount of solvents and reagents required per sample analysis and the energy consumption and wastes generated, investigations on the feasibility of novel tailored and more eco-sustainable solvents are necessary to increase the performance and environmental friendliness of the costly current monitoring programs. Finally, the widespread use and incorporation of powerful separation-plus-detection instruments to these laboratories as routine analysis instruments should enhance not only the performance of the developed methodologies but contribute to fully exploit their high throughput potential and ensure promote early identification of potential and emerging risks.

Similar approaches need to be taken into account for pathogens, as multi-pathogen procedures are also required when setting-up more automated procedures. Additional requirements, such as the need to understand the role of the viable but non-cultivable bacteria in the contamination of food or the detection of genomic material, need to be addressed in order to assess the potential viability/infectivity of the targeted pathogen.

3.4.2. Global approach for the evaluation/measurement of food toxicity (cocktail effect).

The development of new tools or devices to guarantee the protection of human life and health from three types of hazards in food: physical, biological, chemical, and their chemical combination is urgently needed. EU legislation deals not only with individual substances but with the mixture of several hazardous substances, either intentional mixtures, mixtures originating from a single source, or mixture of chemicals originating from multiple sources and through multiple pathways. Intentional mixtures are manufactured and formulated products that are marketed. Interactions of chemicals in mixtures are difficult to predict, particularly for long-term effects. This is due to the complexity of the problem, the large numbers of anthropogenic and natural chemicals involved, and the amount of data needed to describe the toxicological profiles and exposure patterns of these chemicals in humans, companion and farm animals and wild species present in the environment. Research is needed to define criteria that predict synergy, potentiation, or supra-additive effect as well as antagonism, inhibition, or masking. EFSA has identified as a key priority area the development of consistent methodologies for combined exposure to multiple chemicals (More et al., 2019a). It has a chemical hazards database: OpenFoodTox (Dorne et al., 2017) for individual substances but not yet for the chemical combinations. One online survey about the awareness, understanding, and risks of chemical mixtures by consumers from Belgium has demonstrated their high level of understanding as well as the degree of concern about the hazardous effects (McEntaggart et al., 2019). But in general, the knowledge about the risks of chemical mixtures is still low. In 2016, EFSA announced a public consultation to develop a harmonized methodology for risk assessment of chemical mixtures. The coordinated framework consists of problem formulation, exposure assessment, hazard identification and characterization, and risk characterization including uncertainty analysis, for both the whole mixture and component-based approaches, describing the steps involved in each of these (More et al., 2019b).

Indeed, the genotoxicity testing has the purpose of identifying if a substance can cause genetic alterations in somatic and/or germ cells. Bacterial reverse mutation test (AMES) is used to identify compounds that can cause spontaneous point mutations, such as base-pair substitutions, deletions, or duplications, which can lead to cancer susceptibility. *In vitro* mammalian micronucleus test (MNT) is used to detect chemicals causing chromosomal aberrations (aneugen) or breakages (clastogen) leading to perturbations in cell division. The resulting micronuclei adjacent to main nuclei are also a sign of genotoxicity. Moreover, for genotoxicity information is also used the weight of evidence approach (WOE), which commonly refers to combining evidence from multiple sources to assess the property under consideration and its corresponding mode of action (MOA).

Qualitative, semi-quantitative and/or non-testing approaches useful for managing unavoidable contaminants or data-poor substances include:

- *in silico* and (quantitative) structure-activity relationship [(Q)SAR] models, which are mathematical models that can be used to predict the physicochemical, biological and environmental properties of compounds from the knowledge of their chemical structure (Cavaliere et al., 2018). There are studies (Frenzel et al. 2017; Benigni et al. 2019) that for the AMES test, all (Q)SAR models generated statistically important predictions, comparable with the experimental variability of the test. However, the precision of the (Q)SAR models for assays/endpoints different from AMES appears to be quite far from being optimum.
- Threshold of Toxicological Concern (TTC) approach, which is a valid methodology to assess the safety of substances of unknown toxicity found in food. This TTC approach is used when there are limited chemical-specific toxicity data and can be used for substances with or without structural alerts for genotoxicity and for cancer and non-cancer endpoints. It is a screening tool to evaluate low-dose chemical exposures and to identify those chemicals for which further data are necessary to assess the human health risk (More, et al. 2019a).
- Read-across, which is defined as a data gap filling technique within an analog or category approach. The first is based on a chemical group with a very limited number of structurally similar substances (usually a target and source substance), and the latter approach is based on a more extensive number of structurally similar analogs (Patlewicz et al., 2014). Generally, a read-across method is satisfactorily applied to predict AMES mutagenicity but less in the case for *in vitro* chromosomal aberrations (Benigni et al., 2019).

Taking into account the nature of the mixture, the employed analytical techniques should be able to detect and to quantify constituents at limits of detection (LOD) and limits of quantification (LOQ), respectively. Besides, it is necessary the information on hazardous properties but avoiding unnecessary animal testing (ECHA, 2016). All these tools should be used in combination with data sharing and waiving (Richardson et al., 2018; More et al., 2019b). Moreover, the society faces new challenges in this area as is the introduction of nanomaterials, where investment is needed to advance the state of practice for new approach methods in responsible research and innovation and regulation. (Shatkin 2020; Comandella et al., 2020).

3.5. New trendy consumption practices and preferences.

Food market globalization, the introduction of novel foods, new manufacturing processes, and the growing demand for minimally processed, fresh-cut, and ready-to-eat products may require a longer and more complex food chain, increasing the risk of microbiological contamination. Thus, novel and complementary food preservation technologies that comply with these demands from "farm to fork" are necessary. Among alternative food preservation technologies, particular attention has to be paid to biopreservation using natural antimicrobials (bacteriocins, bacteriophages, and bacteriophage-encoded enzymes), as previously mentioned.

Although food allergy is actually more often caused by the food itself, some currently consumed food/beverage chemical preservatives (i.e., sulfites, butylated hydroxytoluene, and butylated hydroxyanisole or benzoates) have been reported to trigger allergic reactions. Nowadays, consumers clearly prefer natural preservatives based on the perspective that they are healthier, safer, and provide a better tasting. In this sense, new trendy consumption practices affect the diversity of food consumed and, therefore, potential changes in food intolerance and allergenicity risks, as well as food contamination ways, could be envisaged. Therefore, in some particular cases, the incorporation of new dietary bio-preservatives into a regular diet might trigger allergic or food intolerant reactions in certain individuals. However, given the potential structural diversity and different origins of new bio-preservatives to be consumed and because sufficient experience is not yet available, a case-by-case approach should be necessary to better frame the allergenicity risk assessment.

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SUMMARY FOR EXPERTS

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This volume illustrates the main research issues for the development of an environmental and economical sustainable primary production. An interdisciplinary collaboration between several scientific areas has allowed the study of the future evolution of agriculture, livestock and food production. The first chapters analyze the proper balance between productivity and environmental goals in agriculture and how to reduce its impact on ecosystems. Subsequently, the following chapters discuss the improvement of livestock and aquatic systems. Besides, new approaches in plant health, plant biotechnology and plant breeding are also described according to a future sustainable production. To conclude, the final chapters suggest the novel and future approaches in food production and food safety.

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