The need to enhance crop, livestock and aquatic genetic diversity in food systems

Malou van der Sluis, Niels Anten, Esther van Asselt, Gerbrich Bonekamp, Theo van Hintum, Rolf Michels, Marjon Navarro, Jeanne Nel, Nico Polman, Sipke Joost Hiemstra

Report 1385

WAGENINGEN
UNIVERSITY & RESEARCH

The need to enhance crop, livestock and aquatic genetic diversity in food systems

Malou van der Sluis[1], Niels Anten[2], Esther van Asselt[3], Gerbrich Bonekamp[1], Theo van Hintum[4], Rolf Michels[5], Marjon Navarro[6], Jeanne Nel[7], Nico Polman[5], Sipke Joost Hiemstra[1]

1 Wageningen Livestock Research
2 Plant Sciences, Wageningen University
3 Wageningen Food Safety Research
4 Wageningen Plant Research
5 Wageningen Economic Research
6 Wageningen Food & Biobased Research
7 Wageningen Environmental Research

This research was carried out by Wageningen Livestock Research and subsidised by the Dutch Ministry of Agriculture, Nature and Food Quality, within the framework of KB Research theme 'Food security and Water' (project number KB-35-007-001).

Wageningen Livestock Research
Wageningen, August 2022

Report 1385

WAGENINGEN
UNIVERSITY & RESEARCH

van der Sluis, M., N.P.R. Anten, E.D. van Asselt, G. Bonekamp, T.J.L. van Hintum, R. Michels, M.E. Navarro, J.L. Nel, N.B.P. Polman, S.J. Hiemstra, 2022. *The need to enhance crop, livestock and aquatic genetic diversity in food systems.* Wageningen Livestock Research, Public Report 1385.

Short summary Biodiversity loss is a global threat and biodiversity for food and agriculture is particularly relevant in the context of our food systems. This report discusses the current status and trends of crop, livestock and aquatic genetic diversity, in relation to food systems. The impact of decreasing or enhanced use of crop, livestock and aquatic genetic diversity – within and across species and varieties – is discussed in relation to four different food system dimensions: 1) safe and healthy diets, 2) food security, 3) inclusiveness and equal benefits, and 4) sustainability and resilience. To this end, both a literature review and stakeholder and expert interviews were used. We provide a conceptual framework for assessing trade-offs of different measures and strategies for increased use of crop, livestock and aquatic genetic diversity. We furthermore highlight key topics for future research and policy recommendations in this area.

Korte samenvatting Verlies van biodiversiteit is een wereldwijde bedreiging en met name de biodiversiteit voor voedsel en landbouw is relevant in de context van onze voedselsystemen. Dit rapport bespreekt de huidige status van, en trends in, de genetische diversiteit in gewassen, vee en aquatische soorten, in relatie tot voedselsystemen. De impact van afnemend of toenemend gebruik van genetische diversiteit in gewassen, vee en aquatische soorten – binnen en tussen soorten en variëteiten – wordt besproken in relatie tot vier dimensies van het voedselsysteem: 1) veilige en gezonde voeding, 2) voedselzekerheid, 3) inclusiviteit en gelijke voordelen, en 4) duurzaamheid en veerkracht. Hiervoor is gebruik gemaakt van zowel een literatuuronderzoek als interviews met stakeholders en experts. In dit rapport bieden we een conceptueel kader voor het beoordelen van de wisselwerking tussen verschillende maatregelen en strategieën voor het vergroten van het gebruik van genetische diversiteit in gewassen, vee en aquatische soorten. Verder benoemen we een aantal belangrijke richtingen voor toekomstig onderzoek en beleidsaanbevelingen op dit gebied.

This report can be downloaded for free at https://doi.org/10.18174/575252 or at www.wur.nl/livestock-research (under Wageningen Livestock Research publications).

Wageningen Livestock Research Report 1385

Contents

Summary

Biodiversity loss is a global threat and biodiversity for food and agriculture is particularly relevant in the context of our food systems. This report discusses the current status and trends of crop, livestock and aquatic genetic diversity (CLAGD), in relation to food systems. The impact of decreasing or enhanced use of CLAGD – within and across species and varieties – is discussed in relation to four different food system dimensions: 1) safe and healthy diets, 2) food security, 3) inclusiveness and equal benefits, and 4) sustainability and resilience. To this end, both a literature review and stakeholder and expert interviews were used. We furthermore highlight key topics for future research and policy recommendations in this area.

Overall, the literature indicated that genetic diversity, in particular the use of genetic diversity in food systems, shows a declining trend and that clear consensus on standards for measuring and monitoring CLAGD is lacking. Lack of agreed and proper indicators and data collection are considered to be limiting factors in this. Adequate conservation and sustainable use of CLAGD is pivotal, yet despite increasing efforts, major gaps remain. In the long run, the decline in CLAGD can pose serious threats, including increased disease and pest vulnerability, reduced resilience and insufficient diversity in breeding crops or animals for other or changing systems or circumstances. Decreased or enhanced use of CLAGD may (indirectly) affect all four food system dimensions. The expert and stakeholder interviews highlighted several major barriers for addressing the decline in CLAGD, including the observation that stakeholders and major supply chains respond to retail and consumer or societal demands (for example from NGOs), but that substantial incentives for increasing biodiversity, including enhanced CLAGD in food systems, from consumers, or regulations, are currently lacking. It appears that supply chains and consumers generally aim for an increased sustainability of production in the broad sense, with limited direct attention for species and breed diversity within systems, and increased genetic diversity is not seen as a goal in itself. Moreover, it is not clear who should or could initiate major changes or transitions, regarding improved or enhanced use of genetic diversity. Primary production is regarded as the most important part of the food chain where changes can be made. Yet this also requires subsequent links in the supply chain to act, from breeding to the consumer.

Actors and stakeholders involved in designing or developing food systems, would benefit from an assessment framework through which they can assess trade-offs of different measures and strategies for enhancing CLAGD. We developed a first outline for such a conceptual framework, in which we make explicit the trade-offs and synergies of different potential interventions and their effects on different indicators for the four food system dimensions. In this framework, trade-offs and synergies can be shown in relation to each other, to see at a glance what interventions have overall positive effects and are therefore of interest for broad implementation. In the current conceptual framework, only a selection of measures is included as an example. In the future, this framework can be developed into a more structured overview of measures and their expected outcomes (indicators by food system pillar).

Key topics for future research and policy recommendations include actions on the general topics of 1) data and monitoring (e.g., implement standardised guidelines and indicators for monitoring of CLAGD), 2) research (e.g., research should aim to address the problem as a whole, instead of separately studying subcomponents of the issue), 3) societal awareness and market incentives (e.g., increase consumer awareness for the importance of CLAGD in food systems and promote diversity through marketing), 4) technology (e.g., more attention for and investment in technologies that can handle diversity), 5) public policies, regulations and both public and private financial incentives (e.g., develop and implement regulations and incentives to maintain and to make available a broader range of species and quality varieties or breeds to producers and value chains), and 6) commercial parties in the food system (e.g., breeding companies could broaden their portfolio). It is important to keep in mind that different interventions may interact, and, therefore, it is recommended that close attention is paid to the effects of these interventions on other components of biodiversity or food systems as well, to determine whether there are no negative or unwanted side effects of these interventions.

1 Introduction

Biodiversity is the variety of life at genetic, species and ecosystem levels (FAO, 2019a). Biodiversity thus encompasses three levels: 1) ecosystem diversity, defined as the variety of biotic communities, diversity of habitats, ecological processes within an ecosystem, or the patterns found within a landscape, 2) species diversity, defined as the variety and abundance of different types of organisms (often including variety in their functional traits) that inhabit an area, and 3) genetic diversity, defined as the combination of different genes (or alleles) found within a population of a single species (Hammen and Settele, 2011). The subset of biodiversity that contributes in one way or another to agriculture and food production is generally termed 'biodiversity for food and agriculture' (**BFA**) (FAO, 2019a). BFA includes plant (crop) genetic resources, animal (livestock) genetic resources, forest genetic resources, aquatic genetic resources and microbial and invertebrate genetic resources (FAO, 2019a). In this report, we focus on crop, livestock and aquatic genetic resources, that is, the genetic diversity between and within species and breeds/varieties of crop, livestock and aquatic species. We refer to this part of BFA as crop, livestock and aquatic genetic diversity (**CLAGD**).

Biodiversity is currently declining (IPBES, 2019) and different drivers play a role in this decline. For example, genetic diversity in crops has decreased over the years, through selection for increased yields and crop quality (Ahlemeyer et al., 2006), and lack of conservation of the lower yielding species. This decline is predicted to continue, due to, for example, changing consumer demands, climate change and pollution. Since not all species can easily adapt to changing environments, this will result in a decline in species (Fatima et al., 2020). Moreover, the distribution of species or breeds used in food production is strongly skewed, with a few species constituting the largest part of production.

The increase in agricultural production has been associated with global dominance of a limited number of crops. Out of a global estimated 391,000 vascular plant species known to science (RGB Kew, 2016), only around 6,100 species are cultivated for food (IPK, 2021), and only 200 of these had significant production levels at a global scale in 2014 (FAO, 2019a). Moreover, 66% of all crop biomass production worldwide comes from only nine crop species: sugar cane, maize, rice, wheat, potatoes, soybeans, oil-palm, sugar beet and cassava (FAO, 2019a).

In the livestock sector, the number of terrestrial animal species used is also small. A total of 38 species are recorded in the Global Databank for Animal Genetic Resources (FAO, 2019a) and, of these species, several are again used more than others: for instance, six species, poultry (37%), pigs (35%), beef cattle and buffalo (21%), and sheep and goats (5%), make up 98% of the global meat production (Our World in Data, 2021). In terms of milk, cattle (81%), buffaloes (15%), goats (2%), sheep (1%) and camels (0.5%) together make up 99.5% of the world milk production (FAO, 2022).

In aquaculture, around 1,800 aquatic species (about 1% of the species globally found; based on numbers reported in FAO (2019a)) were harvested by capture fisheries globally in 2016 (FAO, 2019a) and based on an analysis from 2015, it appeared that 33.1% of fish stocks were estimated to be overfished, 59.9% were maximally sustainably fished and only 7.0% were underfished (i.e., had an abundance above the level corresponding to the maximum sustainable yield; FAO, 2018a).

Overall, these numbers highlight the limited or skewed representation of species in agriculture, aquaculture and fisheries, but there are some nuances to these general trends. Particularly in food systems, optimal use of the genetic diversity within species is as important as the number of species used and their contribution to total production. Increased specialization and intensification in agriculture generally goes hand in hand with the dominance of a limited number of high-performing breeds or varieties. As a consequence, a major part of genetic diversity within species of livestock and crops is at risk of extinction. The current state of conservation and use of crop, livestock and aquatic genetic resources will be summarized in this report.

BFA currently receives a lot of attention. For example, One Planet Business for Biodiversity (OP2B) was launched at the United Nations Climate Action Summit in New York in September 2019, which is an international, cross-sectorial business coalition on biodiversity in agriculture, aiming to drive change and action regarding cultivated and natural biodiversity protection and restoration (OP2B, 2021). Moreover, the Commission on Genetic Resources for Food and Agriculture of the Food and Agricultural Organization of the United Nations is addressing BFA, aiming to reach international consensus on strengthening policies for sustainable use and conservation of genetic resources for food and agriculture, as well as fair and equitable sharing of benefits derived from their use (FAO, 2021a). Among other elements of biodiversity, the conservation and sustainable use of BFA is also within the scope of the Convention on Biological Diversity (CBD, 2010).

The first global assessment of biodiversity for food and agriculture (FAO, 2019a) states unequivocally that "*biodiversity for food and agriculture is indispensable to food security [..]*". It highlights that biodiversity is needed at all levels - genetic, species and ecosystem - to address the challenges in our food systems. For example, it is stated that biodiversity may reduce dependency on external inputs that may be costly or harmful to the environment, and may generally improve the resilience of production systems and livelihoods. However, the exact role of biodiversity, in terms of risks and opportunities, in our food systems requires further investigation.

This report focusses on the current status and trends in CLAGD, provides an inventory of what is known about the role of CLAGD in our food systems, for four different food system dimensions (safe and healthy diets, food security, inclusiveness and equal benefits, and sustainability and resilience (Van Berkum et al., 2018); **Figure 1**), and highlights key topics for future research and policies in this area. This is done through literature review as well as stakeholder and expert interviews. It starts with a broader outline of the current state of use and conservation of CLAGD, followed by a description of the four food system dimensions. Then, the role of CLAGD for each of these four dimensions is discussed separately. This is followed by an overview of the outcomes of stakeholder and expert interviews. Finally, a conceptual framework of potential interventions related to the use of CLAGD, and their respective consequences for the four food system dimensions, is presented, as well as final conclusions and recommendations.

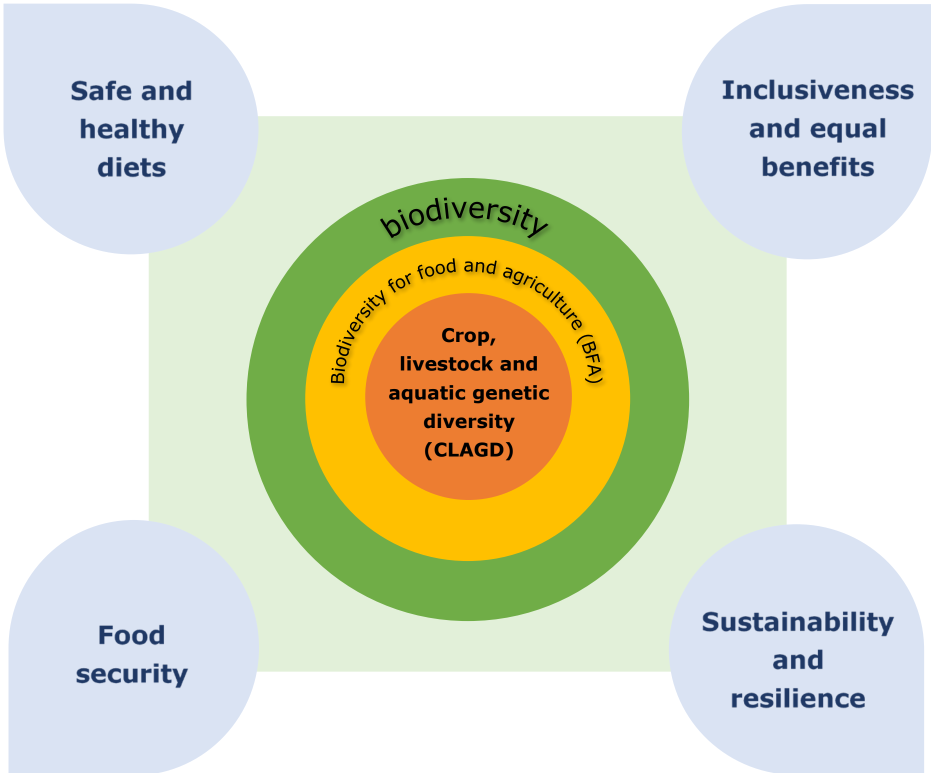


Figure 1 *Overview of crop, livestock and aquatic genetic diversity in relation to four food system dimensions.*

2 State of use and conservation of BFA

Many components of BFA seem to follow a declining trend. Major global drivers for changes in BFA include changes in climate, international markets and demography (e.g., population growth). These global drivers may give rise to more immediate drivers of change as well, such as pollution or land use changes. It is important to note, however, that the situation is complex and that different drivers may interact (FAO, 2019a). Adding to the complexity is the lack of data on specific resources or areas. In terms of genetic and species diversity, a range of different aspects can be monitored regarding the state of use, and the extent and frequency of monitoring varies largely between domains and across the world.

Within BFA, the conservation and sustainable use of CLAGD is pivotal. This is highlighted in the second Sustainable Development Goal - End hunger, achieve food security and improved nutrition and promote sustainable agriculture, Target 2.5, which is to "*maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed*" (United Nations, 2015). To monitor this target, three different indicators were developed for plants and animals. For plants, the indicator Number of plant genetic resources for food and agriculture secured in medium or long term conservation facilities (*ex situ* in gene banks) was introduced for monitoring on a global level (indicator 2.5.1a). The number of plant genetic resources secured has been growing over the past years and had reached a value of 5.7 million in 2020 (FAO, 2021b). For animal genetic resources (farm animals), two different indicators were introduced: 1) Number of animal genetic resources for food and agriculture secured in medium or long term conservation facilities (*ex situ* in gene banks; indicator 2.5.1b), and 2) Proportion of local breeds classified as being at risk of extinction (indicator 2.5.2). Regarding the first indicator, out of a global total of 7,700 registered local breeds (including extinct ones), only 8.7% have some genetic material stored, and of these only 2.7% have sufficient material stored to allow them to be reconstituted. Regarding the second indicator, 74% of the breeds are deemed at risk of extinction (FAO, 2021b).

However, there appears to be no clear consensus on how to exactly measure and monitor the state of conservation and use of CLAGD. The sustainable development goal (**SDG**) target 2.5 and the indicators used for monitoring genetic resources seem to focus mostly on the conservation of genetic resources, rather than on its use in the field or on farm. Moreover, the SDG indicators do not take into account the genetic resources of aquatic species. Ideally, different approaches for conservation and use of crop, livestock and aquaculture genetic resources are combined and complementary. However, despite increasing efforts to conserve genetic material, major gaps remain. In the remainder of this section, we will discuss in more detail how the level of use of diversity is measured, what the current status of use is, what the trends and drivers are in the use of diversity, and what the state of conservation is, for crops, livestock and aquaculture separately. The observations are also summarized in **Tables 1** and **2**.

2.1 State of use and conservation of crop genetic resources

For crops, the number and abundance of species used in agriculture is often used as the main indicator of the status and trends of biodiversity. A widely applicable indicator for within-species diversity is not yet available (FAO, 2019a). Measuring within-species diversity could, however, be informative for trends in the diversity grown in agricultural systems, and could for example be achieved through metrics such as allelic diversity or richness, or nucleotide diversity (Hughes et al., 2008). However, even though DNA-based technologies are developing fast and are becoming cheaper, and the availability of genomic data is expanding rapidly, the required frequency and scale for genetic diversity monitoring are not always reached (Dulloo et al., 2021). The need for more or better indicators of genetic diversity has been recognized (e.g., in regards to the Convention on Biological Diversity (Hoban et al., 2020)).

Table 1 *Summarizing overview of state of **use** of CLAGD.*

	Crops	Livestock	Aquatic species
Indicators	• At species and varieties level • Richness and abundance of species	• At breed level • Richness and abundance of breeds • Risk status of breed (SDG indicator)	• Mainly at species level • Richness and abundance of species • Status of marine fish stock (over/under fished) • Number of species farmed in aquaculture
Status	• 6,100 species for cultivation, only 200 with significant production levels globally • 66% of all crop production worldwide comes from only nine crop species	• 38 domesticated species for agriculture • 600 local breeds already extinct, 26% at risk of extinction, 7% not at risk, 67% unknown	• 1,800 species being captured by fisheries • 694 species farmed in aquaculture • 33% of fish stocks overfished • More species farmed now than ever before
Trends	• Global diversity is declining, also diversity within farmers' fields	• Declining	• Percentage of fish stocks at sustainable level has declined
Drivers	• Change from traditional to "modern" production system • Land clearing**,** overgrazing, and environmental degradation (FAO, 2010)	• Global growth in demand of animal-source food • Changing production systems • Disease epidemics	• Increasing wealth, urbanisation • Habitat loss, pollution • Introduction of invasive species

Table 2 *Summarizing overview of **conservation** state of CLAGD.*

	Crops	Livestock	Aquatic species
Indicators	• At species, variety and gene bank accession level • Links with geographic distributions and habitats • Attempts to combine in situ and ex situ conservation data • SDG 2.5.1: "Plant genetic resources accessions stored ex situ (number)"	• Breed level within relevant species • SDG 2.5.1 and 2.5.2: "Number of local breeds for which sufficient genetic resources are stored for reconstitution" and "Proportion of local breeds classified as being at risk as a share of local breeds with known level of extinction risk"	• Mainly species level, e.g., number of farmed or fished species (FAO, 2019b) • ***In situ*** protected areas • ***Ex situ*** conservation both in vivo and in vitro (e.g., live gene banks and breeding centres) • Breeding programs and ex situ methods need to be further developed
Status	• Global holdings in 2020 reached 5.7 million accessions conserved in 831 gene banks (United Nations, 2021) • Major gaps in ***ex situ*** conservation of 93% of crop wild relatives in US (Khoury et al., 2020)	• Risk status of 61% of local breeds unknown • Of limited number surveyed, 74% deemed at risk of extinction (United Nations, 2021) • Material in gene banks only sufficient for breed reconstitution for 203 out of 7,700 local breeds (United Nations, 2021)	• Most reporting countries have ***ex situ*** in vivo conservation programmes, together covering approx. 290 species (FAO, 2019b)

In the absence of more accurate indicators, the level of genetic erosion (i.e., loss of genetic diversity (FAO, 1997)) and consequent genetic vulnerability (i.e., a condition resulting from a uniform susceptibility of a crop to a pest, pathogen or environmental hazard due to its genetic constitution (FAO, 1997)) resulting from a decline in genetic diversity in agricultural systems can be approached by the extent to which single varieties are dominant across large areas of land (FAO, 2019a). In terms of use of diversity, currently out of a global 391,000 known vascular plant species (RGB Kew, 2016), only around 6,100 species are cultivated for food (IPK, 2021), even though it has been suggested that there are more than 50,000 edible plants in the world (MacEvilly, 2003). Of the species that are cultivated for food, only 200 have significant production levels at a global scale (FAO, 2019a). Moreover, 66% of all crop food biomass production worldwide comes from only nine crop species: sugar cane, maize, rice, wheat, potatoes, soybeans, oil-palm, sugar beet and cassava (FAO, 2019a). As mentioned earlier, a global analysis assessing the diversity within species is lacking, but it is clear that the diversity of crop wild relatives has decreased in some areas, especially those where climatic conditions are changing and species migration is limited by ecogeographical barriers (FAO, 2019a). Also the diversity in farmers' fields seems to be decreasing for some crops in certain areas and countries (FAO, 2010), although it must be noted that others report no substantial reduction in the regional diversity of crop varieties released by plant breeders (van de Wouw et al., 2010). Several studies furthermore report that there is erosion of crop genetic diversity (e.g., Mathur (2011)). Khoury et al. (2020) performed threat assessments for 600 native taxa of crop wild relatives and observed that 28% may be vulnerable, 50% may be endangered and 7.1% may be critically endangered in their natural habitats. One driver for the reduction in diversity is the conversion from traditional to 'modern' production systems, which is noted to often lead to genetic erosion, being associated with poor conservation of traditional landraces and varieties, which hence have become rarer or disappeared (Dulloo et al., 2021; FAO, 2019a). Land clearing, population pressure, overgrazing and environmental degradation are additional factors contributing to genetic erosion (FAO, 2010).

Plant genetic resources are mostly conserved *ex situ* in gene banks, in the form of seeds, living plants, plant tissue or pollen (FAO, 2010). The status of conservation varies largely and depends on the country and crop. For major crops like wheat and rice, a large part of the genetic diversity is represented in collections, but for many other crops and wild relatives extensive collections are still lacking (FAO, 2010). For instance, in a United States inventory it was indicated that there were major *ex situ* conservation gaps for 93% of the wild relatives (categorized as urgent or high priority) (Khoury et al., 2020). Moreover, clear documentation of gene banks is often missing (FAO, 2010), making it difficult to get an exact overview of the diversity that is conserved. Furthermore, the reliability of the gene bank in terms of conservation of, and access to, the material varies between gene banks and is often very low, although objective data about the status of *ex situ* conservation are not available. Nonetheless, the available data suggest an increase of *ex situ* conservation of 20% from 1996 to 2010 (FAO, 2010). In addition to *ex situ* conservation, crops or crop wild relatives are sometimes conserved *in situ*, that is, on farms or in (semi)natural ecosystems (FAO, 2010). Possible indicators for *in situ* monitoring include (changes in) geographical distribution, habitat diversity, species richness, species abundance, phenology and biotic interactions, and threat status (discussed in Dulloo et al. (2021)). An indicator combining information for functional wild plants was developed by Khoury et al. (2019). This indicator, termed 'comprehensiveness of conservation of useful wild plants', measures the extent of conservation of wild plant species in gene banks and other *ex situ* living plant repositories, as well as in protected areas, and combines the species level results to create the indicator at various scales (Khoury et al., 2019).

2.2 State of use and conservation of livestock genetic resources

For animal genetic resources, diversity is often measured at the breed level, not the species level. The indicator for diversity that the FAO uses, is the proportion of breeds being at risk of extinction. Breeds are categorized as 1) at risk, 2) not at risk, 3) extinct, and 4) of unknown risk (FAO, 2019a). However, this approach treats all breeds equally, regardless of their significance to the overall diversity of the species (FAO, 2019a). Moreover, the within-breed genetic diversity is not considered, which would be informative for genetic erosion estimation. In terms of use of diversity, the number of terrestrial animal species used in agriculture is low. In total, 38 species are recorded in the Global Databank for Animal Genetic Resources (FAO, 2019a) and several are used more than others: for meat production, poultry (37%), pigs (35%), beef cattle and buffalo (21%) and sheep and goats (5%) have the highest contributions to the total global meat production (Our World in Data, 2021). In terms of milk, cattle (81%), buffaloes (15%), goats (2%), sheep (1%) and camels (0.5%) together make up 99.5% of the world milk production (FAO, 2022). From an analysis in 2018, it appeared that of the 8,803 livestock breeds that are recorded by the FAO, 7,745 breeds were classified as local breeds (i.e., present in only one country) and 594 of these are extinct (FAO, 2019a). Of the remainder of the local breeds, 26% were classified as being at risk of extinction, 7% was not at risk and the status of 67% of the local breeds was unknown (FAO, 2019a). Clear conclusions regarding trends and drivers in the use of diversity are lacking. A major reason for the difficulty in monitoring the risk status of breeds in many countries is the lack of regularly updated data on the size and structure of breed populations (FAO, 2019a). Keeping the limitations in the state of reporting in mind, there does seem to be a small decrease in the percentage of local breeds classified as being at risk (29 to 26%), in the period from 2006-2014 (FAO, 2019a). At the same time, however, the percentage of local breeds with unknown status increased. Major challenges for the sustainable management of livestock genetic diversity include economic drivers and changing market demands, weaknesses in animal genetic resource management programmes, policies and institutions, degradation of (or limited access to) natural resources, climate change and disease epidemics (FAO, 2015).

For conservation of animal genetic resources, both *in situ* and *ex situ* approaches are used, that are generally considered complementary to each other (FAO, 2019a). The *in situ* conservation of animals is defined as support for continued use by livestock keepers in the production system in which the livestock evolved or are now normally found and bred (FAO, 2015), and in the broader sense also includes actions targeting feral populations or the wild relatives of domesticated animals (FAO, 2019a). Actions related to in situ conservation strategies might involve increasing the demand of products and services from at-risk breeds, supporting the livestock keeper, and activities focused on the breeding programme (FAO, 2019a). Ex situ conservation of animals can be done either *in vivo*, defined as maintenance of live animal populations not kept under their normal management conditions and/or outside the area in which they evolved or are now normally found, or *in vitro*, defined as conservation under cryogenic conditions including the cryoconservation of embryos, semen, oocytes, somatic cells or tissues having the potential to reconstitute live animals at a later point in time (FAO, 2015). As reported for SDG 2.5 in the year 2021, the risk status of 61% of local livestock breeds was yet unknown, and of the limited number of local livestock breeds that was surveyed, 74% are considered at risk (United Nations, 2021). Only for 203 out of a total of 7,700 local livestock breeds, sufficient material is stored in gene banks for reconstitution of the breed (United Nations, 2021). This highlights that there are still large gaps in the conservation of animal genetic resources.

2.3 State of use and conservation of aquatic genetic resources

FAO (2019b) defines aquatic genetic resources as encompassing DNA, genes, chromosomes, tissues, gametes, embryos and other early life history stages, individuals, strains, stocks and communities of organisms of actual or potential value for food and agriculture. They include both farmed aquatic species and their wild relatives. The genetic distinction between wild and farmed populations is for many species less clear than in the two other categories, crops and livestock, as there has been less breeding and there is often significant gene flow between populations in aquatic systems. In the aquatic sector, measurement of diversity at the intra-species level is less developed than for crops and terrestrial animals (FAO, 2019a). The status of marine species that are targeted by fisheries is defined by the categorisation of species as being overfished, maximally sustainably fished or underfished (i.e., with an abundance above the level corresponding to the maximum sustainable yield; FAO, 2019a). For inland fisheries, analysis of this kind is not (yet) available. Currently, the diversity of species used in aquaculture is mainly evaluated by the total number of species that is farmed. However, species diversity is not always a good indicator for genetic diversity, as there is only a weak association between intraspecific genetic diversity and species richness for both marine and freshwater species (Manel et al., 2020). In terms of use of diversity, around 1,800 aquatic species were harvested by capture fisheries globally in 2016 (FAO, 2019a). Based on an analysis from 2015, it appeared that 33.1% of marine fish stocks were estimated to be overfished, 59.9% were maximally sustainably fished and 7.0% were fished below that maximum level (FAO, 2018a). In 1974, only 10% of the stocks were overfished, so the number of species being overfished is rising (FAO, 2018a). Nowadays, 694 species are farmed in aquaculture, which is likely more than ever before (FAO, 2019a). Data from other aquatic systems is often lacking and it is therefore difficult to determine the status of species in those systems. Subsequently, limited information on trends in diversity changes is available for those systems. Overall, the main global drivers for degradation of aquatic ecosystems include the growing human population and consequent industrialisation, urbanisation and agricultural intensification (Verdonschot et al., 2013).

For aquatic species, there are both *in situ* and *ex situ* conservation efforts. The conservation of aquatic species *in situ* is mainly done through the establishment of protected areas and sustainable fishery methods (FAO, 2019a). Conservation of aquatic resources was for example part of the Aichi Biodiversity Targets under the Convention on Biological Diversity's Strategic Plan for Biodiversity 2011–2020 (Convention on Biological

Diversity, 2021). One of the targets was for governments and other stakeholders to establish protected areas for 17% of their terrestrial and inland waters and 10% of their marine areas by 2020. *Ex situ* conservation of aquatic species, on the other hand, can be done with live organisms, for example through maintenance and captive breeding in zoos, aquaria and live gene banks, or *in vitro* (FAO, 2019a). However, embryos and eggs of aquatic species are difficult to preserve and consequently only the male gamete can be effectively cryopreserved (FAO, 2019a). Of the countries assessed in FAO (2019a), 75% indicated that they implement *ex situ* conservation activities at the national level for aquatic species of national relevance, covering around 290 species in 690 *ex situ* collections.

3 Food system dimensions

To assess the (potential) effect of increasing or decreasing CLAGD in food systems, we use the food systems approach by Van Berkum et al. (2018), to capture different aspects of food systems and their associated challenges. The food systems approach identifies four main dimensions: 1) safe and healthy diets, 2) food security, 3) inclusiveness and equal benefits, and 4) sustainability and resilience (**Figure 2**).

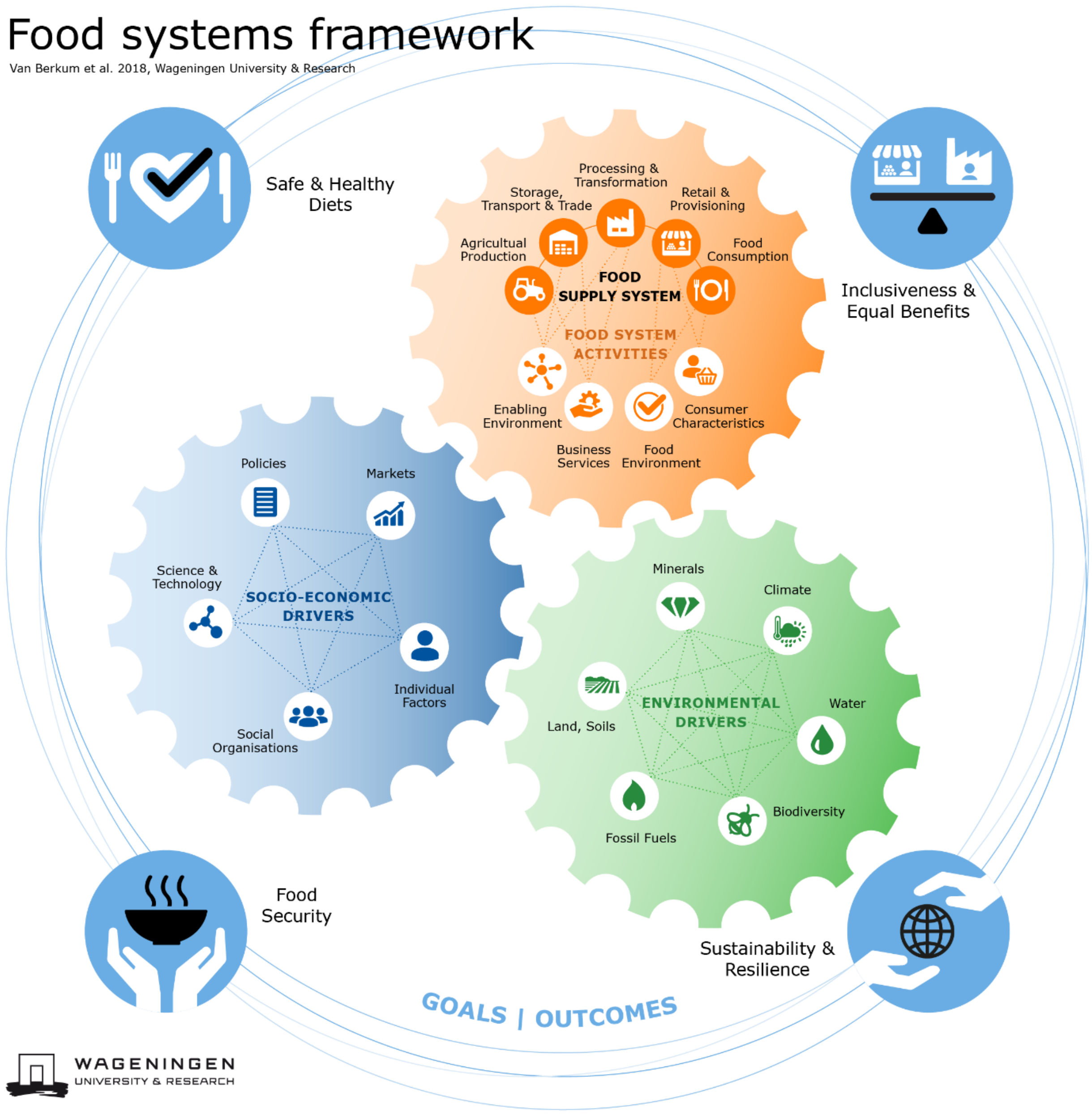


Figure 2 *Infographic of the food systems approach, showing the four dimensions and the interconnectedness between drivers (although the geometry of the cogs unintendingly implies a blockage). From Wageningen University & Research (2021a).*

The safe and healthy diets domain is concerned with the question of how to ensure that our food, nutrition and lifestyle habits result in good health outcomes. The food security domain encompasses the question of how the food system can be organised to ensure that sufficient food is produced safely for everyone and in a growing population. The inclusiveness and equal benefits domain focuses on the question of how the food system can contribute to a level playing field for everyone, including producers and consumers. The sustainability and resilience domain is focused on how the food system can be organised in an environmentally sustainable way, that is resilient to, for example, animal disease crises or trade boycott (Van Berkum et al., 2018). In this respect, a sustainable food system can be defined as a food system that delivers food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised (FAO, 2018b), and resilience can be defined as the ability to cope with perturbations and the rate and speed of recovery after their occurrence (Van Berkum et al., 2018). **Figure 2** shows the food system dimensions and their interconnections. Three categories of drivers are described: 1) the food supply system and food system activities, 2) socio-economic drivers, and 3) environmental drivers, and biodiversity is mentioned as one of the environmental drivers that (indirectly) affects all four dimensions. In the coming sections, the exact role that CLAGD, as a major biodiversity component and being an environmental driver as well as a part of the food system itself, can play in the different food system dimensions will be elaborated on.

4 CLAGD in relation to safe and healthy diets

Safe and healthy diets form the first food system dimension in which CLAGD plays a role. Biodiverse diets are diets that contain a wide variety of diverse food products. Diets can be biodiverse at different levels: food group biodiversity (such as fruits, vegetables and cereals), within-food group biodiversity (e.g., within the food group fruits one has apples, mangos, bananas and more) and within-species biodiversity (e.g., within apples one has Golden Delicious, Elstar and more) (Kennedy et al., 2017). At the national level, food consumption has diversified over the past 50 years. For example, rice was previously the predominant crop in Southeast Asia, but this has now shifted towards other crops. However, these shifts at country level, overall, have led to a more homogeneous crop availability around the globe (Khoury et al., 2014). Empirical evidence in Tajikistan suggests that there are positive linkages between crop diversity and dietary diversity (IFPRI, 2020). Biodiverse diets can be promoted through food-based dietary guidelines (**FBDGs**). FBDGs are a set of guidelines given by governments on how citizens can eat well, for example to promote healthy and sustainable diets (Gonzalez Fischer and Garnett, 2016). To promote biodiversity in FBDGs, the consumption of foods produced in ways that conserve and make sustainable use of biodiversity can be recommended (FAO, 2019a). An associated risk of such an approach is overexploitation of resources to meet the new demands, and therefore close monitoring of ecosystems' health is required (FAO, 2019a).

In this section, we will discuss the effects of reduced or enhanced CLAGD in relation to safe and healthy diets.

4.1 Human disease

Several studies report positive effects of (bio)diverse diets on human health. Positive relationships have been observed between agricultural biodiversity (and associated biodiverse diets) and child anthropometric status, especially regarding the height-for-age z-score (Jones, 2017; Tobin et al., 2019). Moreover, biodiverse diets have been linked to lower probabilities of obtaining chronic non-communicable diseases (**NCDs**) such as cancer and cardiovascular diseases (Johns and Eyzaguirre, 2006). At the global level, an increase in NCDs has been observed due to a shift in diets towards energy-rich and processed products that are based on a limited number of crops (Ebert, 2020; Khoury et al., 2014), and indeed more diverse diets containing fruits, vegetables and nuts have been shown to positively affect human health (Ebert, 2020). The increase in NCDs is, however, more likely related to the type of foods and the processing and preparation of the foods than to the biodiversity of the diet per se. Confounding factors such as lifestyle also impact the prevalence of NCDs (Wagner and Brath, 2012).

4.2 Diet nutritional composition

Although a direct link between diverse diets and human health may be difficult to establish, diversity in the diet has been shown to be positively correlated to the nutritional composition of a diet: increased biodiversity in the diet contributes to achieving the recommended daily intake of nutrients (Kennedy et al., 2005). Nutritional diversity is needed to meet the complex human nutritional needs and a loss in biodiversity results in a reduced intake of nutrient rich foods (Allen et al., 2014). Species and varieties should thus not only be selected based on yields, but also on nutritional composition (FAO, 2017). In this section, we will discuss the relationship between biodiversity and the nutritional composition of diets for crops, livestock and aquaculture.

4.2.1 Crops

Different crop varieties are known to differ in nutritional factors, such as carotenoids, proteins, minerals and vitamins. For example, differences in zinc uptake and translocation are reported in different millet genotypes: 319 finger millet genotypes were analysed and large variation in zinc concentration was observed between the genotypes ranging from 10 to 86 μ/g grain (Yamunarani et al., 2016). Another example are genetic differences that are observed between cowpea varieties regarding protein composition, Fe and Zn levels. These varieties can be used to setup a cowpea breeding line with improved nutritional values (Muranaka et al., 2016). Differences between crops have also been observed. According to the International Fund for Agricultural Development (IFAD), various neglected and underutilized species have high nutritional values. For example, quinoa or millet have similar or higher nutritional values than common commodities such as rice or wheat (IFAD, 2021). Other studies also stress the importance of underutilised crops in their contribution to nutritional security (see e.g., Ebert (2014), Gregory et al. (2018)). Differences between developed and developing countries have been reported, where the latter have more diverse crop portfolios, as is reported for African countries (Johns and Eyzaguirre, 2006). However, in developing countries, agriculture is also becoming more intensive and commercialized, leading to a decrease in traditional dietary diversity and thus impacting the nutritional value of the diet (Johns and Eyzaguirre, 2006; Khoury et al., 2014). A systematic literature review showed that traditional diets containing a variety of local plants and animals contribute to human health by impacting nutritional composition and energy intake, although strong evidence is absent (Penafiel et al., 2011). It has also been reported that, in general, a positive correlation is seen between agrobiodiversity or crop biodiversity and nutrition (e.g., dietary diversity, nutrient adequacy or intake of nutritious foods; Powell et al., 2015). A diet with a high number of species has been shown to positively influence micronutrient intake, which is especially relevant for low and middle-income countries. Both reviews indicate that the relationship between biodiversity and human health has primarily been studied in highly biodiverse ecosystems (in Latin America and Africa), simply because of their high biodiversity, and information for industrial areas is lacking (Penafiel et al., 2011; Powell et al., 2015).

4.2.2 Livestock

The knowledge of the health effects of inclusion of livestock-based products in a mainly plant-based diet is still incomplete, yet recent scientific advances suggest that largely plant-based diets contribute more to improved health than to causing disease, compared to meat-based diets (Sabaté, 2003). In a review of mainly EPIC-Oxford study results, Key et al. (2021) discuss several differences between groups of people consuming vegan, vegetarian or meat-based diets. Plant-based diets are typically linked to low intakes of saturated fat and high intakes of dietary fibre, as well as potentially low intakes of specific micronutrients (e.g., vitamin B_{12}, calcium). Vegetarians and vegans generally have lower BMIs, which can be expected to reduce the risk of obesity-linked disease but increase the risk of disorder linked to being underweight. In terms of major diseases, Key et al. (2021) report that, in comparison to meat-eaters, vegetarians have reduced risks of ischaemic heart disease, diabetes (not BMI-adjusted), any type of cancer (all cancers combined), diverticular disease, kidney stones and cataracts. For vegans in comparison to meat-eaters, the risks of diabetes, all cancers, diverticular disease and cataract were also reduced. However, meat-eaters were observed to have lower risks of stroke, fractures and gallstones (adjusted for BMI) in comparison to vegetarians and lower risks of fractures in comparison to vegans (Key et al., 2021). All-cause mortality was not found to be different between meat-based and vegetarian diets (Appleby et al., 2016). It is important to note, however, that vegetarians and vegans may have different overall lifestyles, and may be more concerned with their health, which could have had a confounding role in these observed effects.

Compositional differences have been observed in local cattle breeds from developing countries. However, conclusions with respect to nutritional values between broadly-classified commercial and local breeds could not be drawn as, apart from breed diversity, management practices (such as diet and slaughter age) also affect the nutritional composition of the meat (Barnes et al., 2012). A study of two different pig genotypes, under identical nutritional and management conditions, has shown that there is variation between pig breeds in meat nutritional composition, for example in terms of intramuscular fat, dry matter, monounsaturated fatty acids, iron and zinc (Palma-Granados et al., 2018). Also within livestock breeds there is genetic variation in nutritional composition of animal products. For example, there appears to be genetic variation in fatty acid profiles of bovine milk (Bobbo et al., 2020).

4.2.3 Aquaculture

Marine biodiversity is indicated to be needed in order to offer healthy seafood diets (Bernhardt and O'Connor, 2021). Information of 801 marine animal taxa was combined and it was shown that, although protein levels were comparable, there were distinct differences in micronutrient profiles. Bernhardt and O'Connor (2021) advocate that, like other animal food products, a diverse seafood diet is a healthier diet fulfilling the needs with respect to vitamins, minerals and essential fatty acids. This is especially true for communities that depend on local seafood harvest. The authors indicated that the nutritional values of a seafood diet increased with species richness, thereby advocating the need for biodiversity. Or vice versa, when biodiversity decreases, a higher seafood consumption is needed in order to meet the recommended daily intakes of the various nutritional factors (Bernhardt and O'Connor, 2021). Co-culturing fish and rice is shown to increase biodiversity and nutritional sources, providing vitamins, minerals, some fatty acids and amino acids (Allen et al., 2014).

4.3 Food safety

There are several studies describing the effect of chemical residues in the environment on a decrease in biodiversity (e.g., Beketov et al. (2013); Néstor and Mariana (2019)), but there is limited information on the effect of a change in biodiversity on the presence of chemical or microbiological hazards in the food. In this section, we summarize what is known and what gaps remain. There are indications that in regions where pesticides are less frequently available, genetic diversity within a field can protect the entire field against pests (Frison et al., 2011) and increased biodiversity has been shown to decrease the need for pesticide use (Allen et al., 2014; Frison et al., 2011; see also **Section 7**). Similarly, rice-based aquaculture was shown to allow for a better control of vectors and pests due to fish biodiversity (Allen et al., 2014). A reduced genetic diversity can lead to increased susceptibility to invading microorganisms, potentially leading to epidemic outbreaks, which may consequently result in a pandemic threatening both animals and humans (Maillard and Gonzalez, 2016; Ostfeld and Keesing, 2013). There are indications that, over time, wildlife diseases and zoonoses have increased, and besides climate change and other factors, biodiversity loss is mentioned as one of the contributing factors (Schmeller et al., 2020). It must be noted that others have reported contrasting effects of increased biodiversity and disease prevalence (Hough, 2014). Disease risk may decrease due to an abundance of host species but could also increase when added species lead to alternative sources of infection or vector meals (in case of vector-borne diseases) (Hough, 2014). However, empirical studies demonstrating the latter are rare and more studies substantiate a decrease in disease transmission with increasing biodiversity (Ostfeld and Keesing, 2013). In general, an increase in biodiversity leads to an increase in resilience towards pests and animal diseases (FAO, 2019a). The mechanisms behind this resilience are complex and are explained in more detail in Ostfeld and Keesing (2013). Wildlife can spread human pathogens and to prevent wildlife access to farms, food safety regulations focus on a decrease in biodiversity. However, increased on-farm biodiversity has been observed to result in a more diverse population of insects and microbes that can rapidly remove wildlife faeces, hereby leading to a decrease in the prevalence of human pathogens (Jones et al., 2019).

Increased biodiversity in grasslands results in the availability of a broader range of forage, which may contain plant toxins. Ragwort, for example, is known to have adverse effects on horses and cows due to the presence of Pyrrolizidine Alkaloids (**PAs**). Such PA-containing plants are usually avoided by grazing animals because of their bitter taste. However, when grasslands are harvested to produce hay or silage, cattle no longer recognise the potential harmful plants and may subsequently consume toxic PAs (Hoogenboom et al., 2011; van Raamsdonk et al., 2015). This not only has detrimental effects on animal health, but may also impact human health, as these compounds are found to be carried over to milk (Hoogenboom et al., 2011). Exposure can be prevented by testing prior to harvest to prevent the presence of PAs in hay or roughage (Raamsdonk et al., 2010). In contrast to the positive effect of biodiversity on nutritional values, a detrimental effect of biodiversity on food safety was observed by Bernhardt and O'Connor (2021). Their analysis showed that most marine species contain low levels of the heavy metals methylmercury, cadmium, lead and arsenic, and only some species contain higher levels of these contaminants. Increasing the biodiversity also increases the exposure to a wider range of contaminants. Differences between the contaminants were observed, but, in general, increased species richness resulted in increased contaminant levels per 100 g. These effects were seen both globally and locally (for Indigenous North American Diets) although the latter effects were smaller (Bernhardt and O'Connor, 2021). Moreover, it has been indicated that, apart from climate change and chemical pollution, structural changes in biodiversity via overfishing and loss of fish abundance have led to disturbances in marine ecosystems, resulting in an increase in harmful algal blooms (Hammen and Settele, 2011). These may lead to increased levels of algal toxins and thus food poisoning through the consumption of affected fish and shellfish.

5 CLAGD in relation to food security

Food security forms the second dimension in which CLAGD plays a role. We follow the FAO (1996) definition of food security: all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life. Often, a combination of food availability (consisting of production, distribution and exchange components), food access (consisting of affordability, allocation and preference components) and food utilization (consisting of nutritional value, social value and food safety components) is considered when food security is discussed (van Berkum et al., 2018).

5.1 Trends in food security

Both food systems and food security in the 21st century are fundamentally characterised by social and economic change (Ericksen, 2008). Ericksen (2008) distinguishes a range of characteristics of this change, including intensification of food production, the growth of processing and packaging of food products, corporate concentration in retailing and distribution, and the rising influence of large numbers of urban consumers. Even though the global food production has increased substantially in the past 50 years (Godfray et al., 2010), approximately 12% of the global population was considered to be severely food insecure in 2020 (FAO, 2021c). Moreover, in the next three decades, the world population will continue to increase, expected to rise to 9 billion in 2050, with the biggest growth occurring in areas that are already facing food insecurity (van Berkum et al., 2018). New projections that take the global COVID-19 pandemic into account indicate that hunger will not be eradicated by 2030 unless strict actions are taken, that especially address inequality in access to food (see also **Section 6**; FAO, 2021c).

The FAO (2021c) has reported that the major drivers of food insecurity and malnutrition are 1) conflict, 2) climate variability and extremes, and 3) economic slowdowns and downturns, which are now exacerbated by the COVID-19 pandemic. These drivers continue to increase in frequency and intensity, and are occurring together more often. External (such as conflicts or climate shocks) and internal (such as low productivity and inefficient food supply chains) food system drivers may result in increasing costs of nutritious foods, hereby increasing the unaffordability of healthy diets, especially in combination with low incomes. Such increases in the unaffordability of healthy diets are associated with higher levels of food insecurity. Therefore, transformation of food systems is required, to improve resilience to these major drivers (FAO, 2021c). In the next section, we will discuss, in short, different approaches for this required transformation of food systems.

5.2 Genetic diversity and food insecurity

The FAO (2021c) highlights six pathways for achieving the required food system transformation towards more resilience to the earlier-mentioned drivers (conflict, climate variability and extremes, and economic slowdowns and downturns) and subsequent improved food security:

1. Integrating humanitarian, development and peacebuilding policies in conflict-affected areas
2. Scaling up climate resilience across food systems
3. Strengthening resilience of the most vulnerable to economic adversity
4. Intervening along the food supply chains to lower the cost of nutritious foods
5. Tackling poverty and structural inequalities, ensuring interventions are pro-poor and inclusive
6. Strengthening food environments and changing consumer behaviour to promote dietary patterns with positive impacts on human health and the environment.

Both food systems and food security are connected to, and dependent on, genetic resources used in crop and livestock breeding (Argumedo, 2021). Especially regarding point 2 of the above pathways, CLAGD plays an import role. As also discussed in the stakeholder interviews (see **Section 8**), low levels of genetic diversity may result in reduced resilience (e.g., regarding drought). The fact that the world's food supplies are dependent on a narrowing diversity in crop species, can therefore be considered a potential threat to food security (Khoury et al., 2014). Global challenges in food systems are interdependent and different elements of food systems interact with one another. Without taking sufficient account of changes in the natural, technical and social systems surrounding it the food system different levels, a food system can be highly vulnerable as a result of a one-sided emphasis on expanding production ecosystem services, like food and fibre production or short-term cost minimization in the value chain. The balance within the food system can be disrupted by processes such as specialisation, that is, a focus on production methods which rely on single animal breeds and monocultures (i.e., less CLAGD), with their attendant risks for food security (e.g., due to pests or disease) and economics (due to large-scale losses). The use of resistant varieties and control measures, such as for maize, make large-scale crop failures less frequent, but do not rule out new outbreaks in the future (Koning et al., 2008). Genetic diversity can contribute to the prevention of disasters like plant diseases (see also **Section 7**) and can spread risks, when multiple breeds or polycultures are implemented (due to only part of the overall production being lost). Lack of resilience to diseases or pests could potentially lead to a global epidemic, which will put food security under pressure. A well-known example of this are bananas (Fuller, 2022): through the use of tissue propagation, identical banana plants producing consistent fruit are created. A large part of the worldwide banana production (around 40%) comes from a single variety, the Cavendish banana. While this is practical for business, the lack of genetic diversity poses them at a great risk for disease, and a potential consequent total wipe out of banana plants. This highlights that more diversity could be beneficial for food safety, both in terms of production levels for farmers and in terms of availability for costumers.

6 CLAGD in relation to inclusiveness and equal benefits

Inclusiveness and equal benefits form the third dimension in which CLAGD plays a role. Food equity (that is, the concept of all people having the ability and opportunity to grow and to consume healthy, affordable, and culturally significant foods (University at Buffalo, 2022)) and inclusiveness are, alongside (healthy) diets, sustainability and resilience, important challenges for food systems (Brouwer et al., 2020). We define inclusive food systems as food systems that "*reach, benefit, and empower all people, especially socially and economically disadvantaged individuals and groups in society*" (Fan and Swinnen, 2021).

6.1 Trends in inclusiveness and equal benefits

The agri-food system is the world's largest economic sector. More than 2 billion people work in the food system, with half of the world's working population active in agriculture (van Berkum et al., 2018). In emerging and developing countries in particular, agriculture continues to be an important livelihood, and therefore also a social safety net. Yet the degree of social inclusion in food systems is often considered insufficient. The food system fails to provide most of these people with an adequate income: three-quarters of all farmers live in poverty (NewForesight & Commonland, 2017). This might result in a vicious circle. Farmers need to be able to pick those varieties that best fit their specific biophysical conditions (climate, pest, weed pressures), their cropping system, and other preferences (Gerullis et al., 2021). Yet, if farmers are unable to make this choice because they lack market or purchasing power, the resulting food system will be less resilient, potentially resulting in more losses and a further reduced income. Furthermore, in 2020 there was a gender gap in the prevalence of moderate or severe food insecurity, with a 10% higher prevalence in women compared to men, which was an increase compared to 2019 when this was 6% (FAO, 2021c). In 2017, around 800 million people suffered from undernutrition, while around 2.1 billion people worldwide were overweight or obese (Fresco et al., 2017).

6.2 Enabling factors and barriers for inclusiveness and equal benefits

Inclusiveness is interconnected with many food system related components, such as poverty, hunger, gender equality, job creation, innovation and infrastructure (World Economic Forum, 2017). Gaupp et al. (2021) note that current food systems bear hidden costs like diseases and deaths, which form a key component to address in the movement towards more inclusive food systems. However, discussions in policy debates on how this can be addressed in an outcome-oriented manner are still largely missing (Gaupp et al., 2021). To achieve more inclusive food systems, there is a need to understand the enabling factors and barriers faced within the food system by breeders, farmers, processors and consumers. Fresco et al. (2017) identify and discuss three critical issues that challenge the current performance of food systems, where one of the most pressing challenges is to develop inclusive and sustainable food systems for the rapidly expanding urban populations:

1) **Rapid urbanisation and the growth of megacities**: By 2050, two-thirds of the world population will live in cities, where economic growth rarely keeps up with the growth of the city, for example resulting in challenges regarding people finding employment, and land and housing allocation pressures.
2) **Requirements for agro-food systems upgrading**: To meet the increased (and changing) demand from the urban agglomerations, local agricultural production needs to diversify. More value can be added to agricultural products through processing, trade and packaging,

and although in many food systems these processes currently result in substantive losses through inadequate handling and infrastructure failures, it also may potentially provide new opportunities for employment.

3) **Management of food access, distribution and price through rural-urban linkages**: Market resilience is vital for enabling a more inclusive food system transformation. However, harvest failures or increasing demands can result in sudden food price spikes. In practice, strategic food reserves are often maintained (at household, regional or national level) to address these insecurities, but this can result in market imbalances if sales are not in line with regular price tendencies. Alternatively, regional trade may offer a solution, and stabilization of food prices can also be achieved through better weather forecasting and insurance strategies for mitigation of losses.

6.3 The relationships between CLAGD and inclusiveness or equal benefits

The relationship between CLAGD and inclusiveness or equal benefits can work in both directions. First, increased CLAGD can contribute to achieving inclusiveness and equal benefits, in multiple ways. As discussed in more detail in **Section 7**, productivity, stress resilience and resource-use efficiency have been shown to increase in natural systems with the number of species in the system (Brooker et al., 2015). This can have a number of positive outcomes regarding inclusiveness and equal benefits. For example, crop diversification can contribute to enhanced crop production (Beillouin et al., 2021), potentially resulting in an increased income for farmers. Moreover, crop diversification can contribute to improved pest and disease control (Beillouin et al., 2021), which may stabilize farmers' incomes through a reduction in losses. Moreover, as mentioned in the previous section (**Section 6.2**), this can also positively affect the stabilization of food prices. Not only crop diversification, but also integration of crops with livestock has been suggested to contribute to improved food security (Lemaire et al., 2014). Empirical evidence also suggests that there are positive linkages between crop diversity and dietary diversity in Tajikistan (IFPRI, 2020). This can be beneficial: when farmers have sufficient resources to be able to access a varied diet, training and basic healthcare, this results in a higher labour productivity (van Berkum et al., 2018). Moreover, empirical evidence suggests that there are positive linkages between crop diversity and agricultural productivity in Kyrgyzstan (IFPRI, 2020).

Secondly, increased inclusiveness or equal benefits can contribute to conservation of CLAGD. If much of the market power in food chains is concentrated in the hands of a small number of traders and retailers who can set the conditions for price and quality (including genetic diversity), farmers risk to be excluded from the value chain if they are not able to meet the conditions of the most influential players in that chain. Yet, through consumer awareness and market promotion, the demand for local or traditional varieties can be increased (e.g., through raising awareness of the value of traditional food species for health and nutrition, or through influencing food policies or research agendas) (Rana et al., 2007). Farmers may receive premium prices for high-quality traditional varieties having specific attributes (Smale et al., 2004) and this can contribute to increased (incentive for) on-farm conservation of these varieties (Rana et al., 2007).

7 CLAGD in relation to sustainability and resilience

Sustainability and resilience form the fourth food system dimension, where a sustainable food system is defined as a food system that delivers food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised (FAO, 2018b), and resilience is defined as the ability to cope with perturbations and the rate and speed of recovery after their occurrence (van Berkum et al., 2018). Resilience was already discussed in the context of food security in an earlier section, but this section discusses the role CLAGD can play in organizing the food system in a sustainable and resilient way. The main focus of this section is a more elaborate study of the potential of crop diversification, but general roles of genetic diversity in livestock and aquaculture will also be discussed.

The general public increasingly demands both affordable food and a clean, biodiverse environment. For example, there is now an EU ban on environmentally malign neonicotinoid insecticides. This means that there is an urgent need for a transition towards robust environmentally benign agricultural production systems, in which biodiversity and resilience are the starting point to counter external threats (Vision report Ministry of Agriculture, Nature and Food quality, 2019; The European Green Deal, European Commission, 2019). Smart use of biodiversity provides major opportunities to address this challenge. Ecological research on natural systems has shown that productivity, stress resilience and resource-use efficiency increase with the number of species in the system (Brooker et al., 2015). Similarly, it is known that genetic variation within species can contribute to resistance and resilience in relation to (a)biotic stress.

7.1 The potential of crop diversification

Crop diversification can contribute to, among other things, enhanced crop production, associated biodiversity (that is, the biodiversity of non-cultivated plants and animals), water quality, soil quality, and pest and disease control (Beillouin et al., 2021), and hereby positively affect resilience and sustainability. Indeed, crop diversification, and especially intercropping and agroforestry, are increasingly mentioned in policy as a means towards the above-mentioned ecological transition towards increased resilience and sustainability of agriculture (see for example Game Changer Green Biodiversity as part of the 8 game changers for production of healthy and safe food (Three Top Sectors for enterprise and innovation in the Netherlands: Agri & Food, Horticulture & Starting Materials, and High-Tech Systems & Materials, 2017)). An important question regards the extent to which genetic diversity in crop-based systems leads to improved performance and how, in turn, this is related to the design of these systems. There are several means through which crop diversification can be achieved (**Table 3**). However, successful implementation hinges on two major questions: 1) does crop diversification contribute to better functioning of crop systems in terms of, e.g., yields, resource-use efficiency, resistance to pests, diseases and weeds, and effects on soil and surface water quality, and 2) if there are indeed significant benefits, what is preventing the broader introduction of crop diversification? In this section we quantitatively address the first question and reflect on the second.

7.1.1 A meta-analysis addressing the effects of crop diversification on ecosystem functioning and services of crops

We reviewed the scientific literature on the effects of crop diversification on ecosystem functioning and services of crops, using an analysis of available meta-analyses. In the last decades, hundreds of experiments comparing more diversified to less diversified crop systems have been performed. Meta-analyses review such studies in a quantitative way, by using results from each study as data and then performing statistical analyses. This can entail calculating averages and confidence intervals to estimate the average direction and magnitude of the effect of crop diversification on crop ecosystem performance across all studies conducted and the variation in this effect. Additionally, a meta-analysis can explore relationships between crop performance and underlying factors, and thus is a powerful tool to determine quantitative trends that may exist across studies. It can, therefore, help us to address the question of how the effects of crop diversification relate to underlying factors. However, there are also drawbacks to meta-analyses, particularly the so-called publication bias, that is, the tendency of journals to accept only papers with significant (large) effects. There are, however, statistical techniques that can, at least to some extent, filter such biases out and nowadays such techniques are required prior to publication of meta-analyses.

Table 3 *Crop diversification approaches discussed in this section.*

Crop diversification approach	Description
Rotations	Growing different crop species after each other in subsequent seasons, thus creating diversity in time. An important reason for doing this is prevention of population build-up of crop specific diseases and pests.
Cultivar mixtures	Growing more than one cultivar simultaneously on the same field (Borg et al., 2018), thus using intraspecific genetic diversity.
Intercropping	Growing more than one crop species on a field, thus using interspecific genetic diversity. The crops can be grown completely mixed (mixed intercropping) or in separate rows or strips (strip-intercropping). The species can either be sown or harvested at the same time (simultaneous intercropping) or in relay (relay-intercropping).
Agroforestry	Systems in which crops (or livestock; see also **Section 7.2**) and trees are grown together, thus using both crop and wild genetic diversity. The trees may or may not produce harvestable goods. In this sense there is some overlap in the definitions of intercropping and agroforestry as multi-species systems containing at least one tree crop could be defined either way.

Table 4 *Effects of different crop diversification types (see Table 3) on agro-ecosystem attributes (biodiversity and several agro-ecosystem functions and services), with the relative effect expressed in percentages and the 95%-confidence intervals of these effects between brackets. Data were obtained from meta-analysis. For each attribute, one or more indicators were considered (see Box 1).*

		Diversification type				
Ecosystem attribute	**Indicator[1]**	**Agroforestry**	**Intercropping**	**Mixed variety cropping**	**Overall mean**	**Reference**
Biodiversity	Relative response	65 (26-105)	7 (3-12)	2 (-12–18)	24 (15–33)	Beillouin et al. (2019; 2021)
Yield	Relative response	35 (12–62)	22 (14–32)	2 (1–3)	14 (8–20)	Beillouin et al. (2019; 2021)
	LER		23 (16–30)			Li et al. (2020); Yu et al. (2015)
	Over-yielding			2 (-1– 12)		Reiss and Drinkwater (2018)
	Over-yielding			3 (-40–60)		Borg et al. (2018)
Fertilizer-use	FNER		47 (20–67)			Xu et al. (2020)
	LER - P uptake		25 (14–37)			Tang et al. (2021)
Soil quality	Relative response	19 (16–23)	11 (5–18)	0 (-25–18)	11 (7–16)	Beillouin et al. (2019; 2021)
Disease control	Relative response	59 (38–62)	66 (40–89)		41 (15–37)	Beillouin et al. (2019; 2021)
	Relative disease reduction		38 (20–75)			Zhang et al. (2019)
Weed suppression	Relative response				60 (13–130)	Beillouin et al. (2019; 2021)
	Relative weed reduction		30 (7–54)			Gu et al. (2021)

[1]See Box 1 for an explanation of these indicators

Box 1. Determining the effect of crop diversification

To determine the effect of crop diversification, one typically compares the performance of a more diversified system to a less diversified one. In the case of intercropping this is usually the performance of the intercrop compared to the mean of the sole-crops of the species that are in the intercrop. For multi-variety crops something similar is done, but then using the mono-variety crops as reference, while for rotations the weighted mean of the constituent crops in the rotation being grown every year could be used. With agroforestry, the comparison is slightly more complex as forest trees in the system may not always produce a harvestable product. Hence, in this case usually the weighted mean performance of only the constituent crops is used.

The simplest response norm that can be used is the ratio between the performances of the more diversified (**Y_D**) and less diversified (**Y_C**) systems (Beillouin et al., 2019; 2021):

Relative response = Y_D/Y_C [1]

where Y_D and Y_C are the performance (e.g., yield or water quality) of the diversified and control system, respectively. However, this measure does not consider the composition of the diversified system. The representation and proportion of constituent types can vary between systems, and the performance of the mixture will thus depend on the proportions in which the more and less performing types are present. There are a number of indicators that account for this effect:

(1) Net performance effect: the absolute difference between performance of a diversified system and performance of the constituent crop types (e.g., sole crops of the species in the mixture in the case of intercrops) (Li et al., 2020).

(2) Land equivalent ratio (**LER**): the area of land needed to produce the same yield as a diversified system if one would grow the constituent crop types (species or cultivars) as sole crops. For example, an LER of 1.3 indicates that one would need 1.3 ha of sole crops (30% more land) to get the same yield as 1 ha of a diversified crop (Yu et al., 2015).

(3) Fertilizer equivalent ratio: similar to LER, but considering the amount of fertilizer needed in sole crops to produce the same yield as in diversified crops (Xu et al., 2020).

(4) Fertilizer equivalent ratio in relation to N (**FNER**): the amount of N fertilizer needed in less diverse systems to produce the same yield as more diverse systems.

(5) The relative pest/disease/weed reduction: the fractional reduction in pests, diseases or weeds in diversified systems compared to a less diverse benchmark (Beillouin et al., 2019; Zhang et al., 2019).

(6) Overyielding: the difference in yield between more and less diverse systems.

Table 4 shows an overview of the results of several meta-analyses that considered the effects of crop diversification on a number of crop performance and ecological parameters (see **Box 1** for an explanation of how the effects of crop diversification can be calculated). To explain, all indices except LER, FNER and LER P uptake, indicate the relative increase (values < 0 indicate a relative decrease) in percentages with the 95% confidence intervals. To give an example, the '65 (26-105)' in top row indicates that agroforestry enhances biodiversity by 65% with the CI between 26 and 105%. The LER and FNER indicate the amount of land (LER and LER-P uptake) or fertilizer (FNER) one needs in monocrops to achieve the same yield (LER and FNER) or phosphorus uptake (LER-P uptake) as in intercrops, in percentages and with 95%-CIs. Hence, '23 (16-30)' in the LER row indicates that one would need 23% more land of sole crops to achieve the same as in intercrops, the '47 (20-67) in the FNER row indicates that one needs 47% more fertilizer to achieve the same yields and the '25 (14-37)' in the LER-P uptake row indicates that one needs 25% more land to achieve the same P uptake. Overall, the effects of crop diversification in **Table 4** are positive. For instance, yields in intercrops are on average 22% higher in intercrops than in sole crops and one would need 23% less land area in intercropping than in sole cropping to obtain the same yields. Similarly, agroforestry and intercropping on average result in a 59-66% reduction in disease incidence. Intriguingly, the magnitude of these effects differs widely, ranging from no effect (effects of mixed variety cropping on soil quality) to an almost 90% increase (improved water quality by agroforestry and intercropping). Furthermore, the effects differ considerably between attributes, being relatively large in the case of water quality and disease and weed control, while being relatively small for soil quality and to a lesser extent yields. Effects on biodiversity and fertilizer-use efficiency seem intermediate. Effects also differ between systems. The effects are largest for agroforestry, followed by intercropping and crop rotations, and are smallest for mixed variety cropping. Finally, there is also large variation among different studies of the attributes in the same system (as signified by the generally wide confidence intervals).

7.1.2 Broader introduction of crop diversification

Clearly, crop diversification can have strong positive effects on crop ecosystem services and the direction of these effects is consistently positive across different services, as well as different types of diversification, as shown by hundreds of studies. This supports the view that crop diversification may contribute to a transition towards a more ecology-based sustainable and environmentally friendly type of agriculture. This raises the critical question why, if crop diversification has such broad benefits, is it (with the exception of crop rotations) so scarcely applied in countries like the Netherlands. A number of factors and knowledge gaps might explain this discrepancy and are discussed here.

7.1.2.1 Biological knowledge gaps

We still do not fully understand how diverse crop systems function biologically, which hampers our ability to optimize the benefits of these systems. As was shown in **Table 4**, there is a large variation in the observed effects, also within attributes and systems. The question that arises from these differences is whether it is possible to design systems that perform at the upper end of the presented ranges (for example, more towards 75% disease reduction by intercropping than the average 38%; **Table 4**), or even beyond. The ecological drivers of performance of diversified systems form one of the biological knowledge gaps. It is still unclear how different ecological mechanisms, such as niche differentiation, facilitation or compensation, contribute to enhancing the performance of diversified systems. Their effects depend on system design (including plant type combinations and planting patterns), as well as crop management. Understanding these interactive effects is critical for optimizing diversification strategies. Some of these processes (e.g., crop pollination and disease and pest spread) operate at large spatial scales (that is, hectares), while many of the other processes (e.g., soil quality and functioning) take years to improve. This might be an explanation for the small reported effects of diversification on soil quality, as most studies are focused on the short term). Another issue is that almost all research on crop diversification has focused on only one of the four diversification types mentioned in **Table 4**. This ignores that the three strategies of spatial diversification (cultivar mixtures, intercrops and agroforestry) can and should be combined with rotations. Experimentally studying mechanisms is highly complex and can be very costly, as it requires experiments that are sufficiently large to encompass spatial diversity and sufficiently long-lasting to include rotations. Such large-scale experiments are difficult and too expensive for individual research groups to set up and maintain. Another biological knowledge gap exists regarding breeding for diversity. Since the pioneering work of Norman Borlaugh in the 1950s, there have been dramatic increases in crop production and yields through crop breeding. That work, however, focused almost exclusively on monocrop systems. Very little similar breeding work has been done to optimize plant traits for diversified systems. There are two main reasons for this. First, breeding for diversity entails that one no longer only needs to optimize traits for a given set of environments, but that one now needs to assess the effects of traits of one crop type as a function of the traits of another crop with which one wants to combine the first crop. In theory, this makes breeding almost exponentially more complex and expensive. Second, as diversified cropping is currently not practiced a lot, there is not yet a sufficiently large market for a larger portfolio of breeding products. Thus, even if breeders would be able to make the required investments to breed for diversity, there are currently insufficient future profits to be made. A third biological knowledge gap concerns the effects of crop diversification on performance stability. While crop diversification is often used to increase performance stability and reduce risks, relatively few studies have aimed to quantify this. That is, the studies reported in **Table 4** all focused on mean performance and generally only covered a few years. Performance stability and, for example, resilience need to be determined over longer periods, such as 5 to 10 years.

Clearly, many of these knowledge gaps deal with a lack of understanding of the long-term effects, of both spatial and temporal crop diversity, as well as of the role of processes acting on wide spatial scales. Addressing these gaps requires joint efforts of various institutions to establish large-scale (that is, hectares), long-term (more than 5 years) system experiments across different ecological zones. Given that such experiments are expensive, crop modelling techniques should be applied to help direct these experiments and help generalize results. The Strip intercropping experiment (Wageningen University & Research, 2021b) conducted by Wageningen University & Research at two sites (Wageningen and Lelystad, both in the Netherlands) is a good example of such an experiment. Furthermore, to support and expedite breeding for diversity, financial incentives are needed to allow breeding companies to invest in research. In addition, as breeding for diversity is so complex and labour intensive, novel statistical techniques and virtual plant modelling tools need to be developed to allow simplification and give direction to these experiments. In this regard, the use of so-called functional-structural plant models (Wageningen University & Research, 2021c) would be very useful, as this allows one to connect variation in physiological and architectural traits and planting patterns of species to system-level crop performance (Evers et al., 2019).

7.1.2.2 Socio-economic, technological and institutional issues

The lack of implementation of crop diversification also has to do with socio-economic and technological issues, as well as institutional issues. A main issue associated with crop diversification is that it generally entails an increase in system complexity. For instance, an intercrop or agro-forest consisting of more than one species requires more complex management than a field consisting of one crop species. Current agro-technology is poorly adapted to such complexity. The reason for this is that technology co-evolved with low diversity systems in a positive feedback loop: technology facilitating higher yields, attracting more farmers to use it, thus creating a market incentive to develop more advanced technology. Redirecting technology development to diverse systems is challenging: there are few farmers that employ diverse systems, so there is a limited market for this technology. At the same time, farmers not wanting to employ these systems might be partly due to no suitable technology being available. Hence, this results in a lock-in. This concept of a lock-in also applies to biotechnology, such as breeding for diversity. Similarly, and this also applies to livestock and aquaculture, the food processing industry has adapted to uniform predictable products increasing efficiency. Through marketing strategies, consumer preferences have then been directed to food produced in this way. This creates a market incentive for further intensification of this system. Again, incentives are lacking to move to more diverse and less predictable products.

Breaking free from these lock-ins requires a set of socio-economical, institutional and technological changes, supported by scientific research aimed at 1) better understanding the socio-economic and institutional feedbacks that have determined the evolution towards the current agricultural system, 2) gaining more insight in the cascading effects of changes in the system, requiring perturbative socio-economic studies in combination with advanced modelling techniques, and 3) better understanding through what trajectories technology can support a transition to crop diversification, as current technology tends to follow a curative approach (i.e., it is designed to solve existing problems) and as technology solves problems, there is less need for self-supportive resilient systems. This last trend could and should be turned around: starting with designing diverse and resilient systems and from there on address questions as to how technology can make such systems feasible. The NWO funded Synergia project (Technology for Ecology, 2021) is an example of a project that addresses this issue.

7.2 Genetic diversity in livestock and aquaculture in relation to sustainability and resilience

Genetic diversity in other production systems in relation to sustainability and resilience of the food system is studied less well than for crop systems. However, some general trends can be observed for livestock and aquaculture systems as well, although additional research will be needed to confirm these trends. For example, Magne et al. (2016) studied single-breed (a specialist or generalist breed) and multi-breed (a specialist and a generalist breed) dairy cattle herds, and observed that the multi-breed herds showed a better trade-off among milk yield, milk fat and protein contents, as well as a better herd reproduction and concentrate-conversion efficiency, than single-breed herds. However, even though there are such benefits to multi-breed farming systems, in practice specialized farming systems that use specialized breeds have become dominant. Also in aquaculture, multispecies systems show potential for increasing yield (e.g., Wahab et al. (2011)). Two underlying processes are suggested by Dumont et al. (2020) to be linked to higher performance of multispecies animal production systems: 1) complementary feeding habits of animal species, and 2) facilitation or competitive exclusion. Not necessarily species differing in what they eat have to be mixed: also species differing in when and/or where they obtain their food can be effective (Dumont et al., 2020). Animal health benefits may also partly underlie the higher performance of mixed-species production systems. For example, some of the carnivorous fish in polycultures may preferentially feed on weaker and ill individuals, which may result in a reduced pathogen load and diffusion in the system (Dumont et al., 2020). However, it is important to pay attention to potential negative interactions that may arise over time (Thomas et al., 2021). For example, if the species have different growth rates, predation risk or trophic competition may result (Thomas et al., 2021). Not only mixture of species within crop, livestock or aquaculture can have benefits. Also, integrated aquaculture-horticulture can be implemented, allowing for the waste of one system to be used as input for the other system (Tripathi and Sharma, 2001). Furthermore, integration of crops with livestock (at all levels, from the field to the region) has been suggested to be beneficial, contributing to improved food security and environmental sustainability, for a number of reasons (Lemaire et al., 2014). First, the spatial and temporal interactions in these systems could potentially result in a better regulation of biogeochemical cycles and a decrease in environmental fluxes to the atmosphere and hydrosphere. In natural ecosystems where the soil-vegetation interactions are stable, there is a strong coupling of C, N and P, both in plants and in soils. Cultivation of soils for annual cropping can result in a decoupling of C and N cycles and in intensive cropping systems, there is an increased risk of N losses to the environment (Lemaire et al., 2014). Moderate levels of grazing can be beneficial, as these can increase soil C and N stocks and soil quality in the long term (Franzluebbers and Stuedemann, 2010). However, more intensive grazing levels may not be beneficial, and more research, also focusing on long-term effects, is needed (Lemaire et al., 2014). Second, the resulting more diverse and structured landscape mosaic of these systems can be beneficial, through the provisioning of more diverse habitats and trophic networks. Third, these systems may have an increased flexibility, allowing better coping abilities for socio-economic and environmental threats (Lemaire et al., 2014).

8 Expert and stakeholder interviews

In addition to the literature study, experts and stakeholders were interviewed regarding their views on the links between enhanced use of crop, livestock and aquatic genetic resources and the four dimensions of the food system, as well as the barriers and leverage points to reach enhanced use of cultivated or domesticated biodiversity. In total, four experts from Wageningen University & Research (on plant, aquaculture, and livestock breeding and production systems) were interviewed. Furthermore, six stakeholders from different areas and companies related to breeding and/or the food production chain were interviewed online, all on separate occasions. **Table 5** shows the topics or questions that were addressed in the interviews.

Table 5 *Topics and questions that were discussed in the expert and/or stakeholder interviews.*

Topics and questions
- What is your understanding of (the relevance of) crop, livestock and aquatic genetic diversity in the food system?
- What trends in genetic diversity do your perceive/observe?
- Which problems/risks are associated with lower levels of genetic diversity (related to food security, sustainability/resilience, safe/healthy diets, inclusiveness/equal benefits)?
- Is your line of work/business strategy trying to address these trends?
- What are perceived barriers to reversing downward trends?
- What are enablers or leverage points to reach enhanced use of crop, livestock, aquatic genetic diversity?
- What are examples of good practices?
- What are follow-up research questions?

The expert and stakeholder interviews indicated that the views on CLAGD and its role(s) in food systems differ slightly, although there appears to be consensus on the main trends and directions in CLAGD in food systems. In this section, some of the main observations from the interviews are highlighted.

8.1 Genetic diversity in the food system

Genetic diversity was noted to be interpreted in slightly different ways by (representatives of) the different experts and stakeholders, which is likely related to their area of expertise (i.e., animal breeders might focus more on individuals, whereas others might look at field- or farm-level diversity). Although we consider genetic diversity *within* and *across* crop, livestock and aquatic species, genetic diversity was generally associated with diversity *within* a species, e.g. genetic diversity was sometimes mentioned to encompass DNA-level diversity within species. For crops, genetic diversity was referred to as different varieties within a crop. However, it was also mentioned that genetic diversity needs to be considered on a space and time scale, and that there nowadays are big monocultures in both space and time. For livestock, genetic diversity both between and within breeds or lines was mentioned to be included. For aquaculture, genetic diversity was mainly interpreted as species richness, as aquaculture was mentioned to be relatively new and therefore there are not (yet) really distinct breeds. In addition, in these systems there is often greater and continuous gene flow between farmed and wild populations, which further diminishes the existence of genetically distinct breeds.

It was also mentioned that there are other layers to genetic diversity in the food system, besides the genetic diversity directly from crops or livestock. The non-productive part of the food system also plays a role. This includes, for example, genetic diversity in soil biota or pollinators, and pests, diseases and their natural enemies, all of which interact with the food system.

8.2 Decreasing trends in genetic diversity in food systems

In all interviews, it was agreed that globally the level of genetic diversity in food systems is decreasing. In one of the interviews, it was mentioned that this might be because our food system is designed to produce sufficient food, focusing mainly on yield and ease of production, and less diversity is easier to manage. However, some nuances were mentioned. First of all, regional differences were mentioned. Regarding breed or variety extinction categorization, in the US and Europe the number of unknowns is less than for developing countries, where the uncertainty of the trends is much larger. Moreover, although diversity has decreased substantially at a global scale, in terms of the food available in supermarkets at local or national level the diversity has increased. Yet it was mentioned that the diversity available in supermarkets in the Netherlands is still small in comparison with China, for example. Furthermore, differences between sectors and species were highlighted. Regarding aquaculture, it was mentioned that decreases in genetic diversity are not such a big issue yet in fisheries and particularly aquaculture (as long as inbreeding is avoided through adequate breeding programs), although there is a threat that the few bred fish species will start dominating aquaculture. For some livestock species, global supply of improved genetics is dominated by few major breeders (e.g., there being only two major global players in chicken breeding). Lastly, some of the stakeholders mentioned that there is a lack of awareness in the industry, or that the industry knows decreasing biodiversity is a problem but argues that there are more immediate problems to solve. However, the interviews pointed out that there are serious risks of decreases in genetic diversity, as will be discussed in the next section.

8.3 Risks of decreases in genetic diversity

Decreases in genetic diversity use can have many (potential) negative consequences. Concerns in relation to low levels of genetic diversity that were mentioned in the interviews included, among other things, insufficient diversity in breeding animals or crops for other or changing systems or circumstances, increased disease and pest vulnerability (especially when chemical products and artificial fertilizer may no longer be available), reduced resilience (e.g., regarding drought, climate change), increased economic vulnerability, loss of local knowledge and culture, and limited food security. In relation to the concern regarding insufficient diversity for breeding animals for other circumstances, it was for example mentioned that "*no one size fits all*", and that diversity is important to allow for future adaptations to lower quality feed or to disease threats, where natural immunity may play a large role. Genetic diversity is needed for risk spreading. Being prepared for unknown future threats was emphasized in this regard, and the available diversity in gene banks might be too limited in this respect. Also for new eating qualities of crops, and for increased yields or returns, genetic diversity is needed. Overall, awareness and understanding of these risks for food systems were mentioned to be lacking.

8.4 Barriers and lock-ins regarding the declining trends in genetic diversity

The challenges or barriers that were mentioned and are faced in relation to addressing the declining trends in genetic diversity are different for the crop, livestock and aquaculture sectors. However, some general observations were mentioned. For example, barriers regarding legislation and economies of scale are applicable to all three sectors. To give one example, labour costs are high in the Western World and therefore often large machines are implemented, but these can often not handle diversity. A challenging question that arose from the expert and stakeholder interviews was that breeds or strains can be considered as a public good, so who should maintain this genetic diversity? Awareness of the issue is increasing, but more realisation of diversity being everyone's responsibility is pivotal. It was mentioned that stakeholders respond to consumer or societal demands (e.g., from NGOs), but that large incentives for increased biodiversity from consumers (as well as from other chains in the food production) or regulations are currently lacking. Moreover, it was mentioned that, often, problems are addressed from one side alone, even though many aspects are of relevance (e.g., climate change, biodiversity, efficiency). Bringing everything together is difficult. Modelling approaches can aid, but cannot capture everything. Here, we will discuss the main challenges that were mentioned for crops, livestock and aquaculture.

8.4.1 Crops

For crops, examples of mentioned challenges include that above-ground phenotyping is well-developed, but tools for underground phenotyping (e.g., of roots) are limited. Furthermore, it was mentioned that farmers tend to want the crops that they can harvest early, due to risks associated with later harvesting. Moreover, it was mentioned that a way to increase diversity is to implement strip cropping (see also **Table 3**), but that breeding for organic agriculture or strip cropping is a small market, making it difficult to step in and, consequently, everyone is waiting on others to do it first (see also **Section 7**). Another important lock-in that was mentioned was optimisation, where everything focuses on the development of subsidies for monocultures, and for example for strip cropping there are no agricultural subsidies. Another difficulty with intercropping that was mentioned, was that in the subsequent steps in the production chain, mixed products are not always accepted or wanted. To give an example for a mix of cereal products: millers do not accept mixed cereals, because they are used to having a certain quantity and quality. In the next step, the bakery might also not appreciate mixed cereals, because they want a certain quantity of a single quality. In such chains, it is difficult to get everyone to adapt. In line with such difficulties, also barriers regarding harvesting were mentioned. For example, genetically different varieties of sugar beet tend to have different shoot heights. This complicates mechanical harvesting, as current harvesters can only automatically harvest plants of uniform height. It was discussed that the past technological developments have influenced current agronomy, and that technology adapted to diversity is needed for the future. Novel technologies, however, can potentially also act to reduce diversity. It was for example mentioned that the introduction of CRISPR for seed companies may result in genetic homogenization: CRISPR focuses on individual genes and is not a multi-gene approach and thus can create a genetically more homogenous product. Another important barrier that was mentioned, are mismatches between research and practice: research often takes place in controlled environments that do not capture the agricultural complexity. It was furthermore mentioned that some of the stakeholders do not directly finance the transition of farmers towards different systems, but that they do provide help through advisors or facilitation of obtaining bank loans. It was mentioned that financial institutes are starting to realise that their financial system is linked to the biophysical world and that this is a great change, but a major barrier was (and still is) that banks meet alternative approaches with scepticism. For example, organic agriculture was mentioned to always have been underfunded. Also, for the stakeholders themselves it was mentioned that they sometimes work with large suppliers that are perhaps more focused on increased productivity as opposed to increased biodiversity. Furthermore, stakeholders might want to make changes or take steps, but this also depends on their shareholders' wishes. Furthermore, initiatives for collecting accessions from all over the world to conserve them according to conservation standards face resistance, as governments do not want to share their genetic diversity, for distrust of its use. Access, benefit sharing and rules or regulations were therefore mentioned as major barriers to reversing the downward trend in genetic diversity, and policy was noted to currently not be effective for improvement. Some crops were mentioned to come with additional challenges. For example, cocoa is a tree crop with a long generation time, making breeding of this crop more difficult and the cocoa market is fragmented and underfunded. Moreover, there is a reluctance to share cocoa clones and moving them around can pose food safety threats. Finally, the current assessment systems that decide on whether or not to allow certain technologies tend to be based on the method rather than the product. For instance, the debate on genetically-modified organisms (**GMOs**) centers around yes-or-no GMOs in general rather than the suitability and safety of the individual GMO products. Furthermore, it was mentioned that optimized feed is easiest to make when the choice of raw materials is broad. However, in the production of animal feed, some countries have only few types of raw materials available and feed producers want certainty: raw materials that are consistently of high quality, always available and affordable. Moreover, for some livestock products, animals are not allowed to have been fed certain raw materials (in large amounts). This is also a limiting factor for potential increase of crop diversity.

8.4.2 Livestock

For livestock, a main barrier that was mentioned was that there is diversity between breeds or lines, but that this diversity also needs to pay for itself, i.e. compensate for the potential additional costs through increased revenues. It was mentioned that companies tend to go for the highest profit in the short term, and thus the relevance of diversity will be valued in monetary terms. It was mentioned that in breeding programs, only a limited number of lines can be kept, as keeping these live animals is a costly investment. Moreover, many traits that might lead to improved sustainability are difficult to value or interpret. An example was mentioned for slower growing turkeys, where the success depends on consumers' willingness to pay more for these products. A related question that was posed was how to find a good balance between price, environmental impacts and animal welfare, for example. Moreover, it was mentioned that also locally, people are dependent on large companies regarding genetics (which is also the case for crops).

8.4.3 Aquaculture

For aquaculture, the use of polycultures (i.e., two or more fish species in the same pods, see also **Section 7**) increases genetic diversity, but it was mentioned that this is not often implemented in commercial cultures, as in practice these systems may be difficult to control and negative interactions between species may arise. Another approach that was mentioned was to implement breeding programs, but local farmers may not be able to afford such breeding programs. Institutions try to help, but there may be insufficient capacity at the local level. Consequently, the lack of local breeding programs was mentioned as a major barrier for increasing genetic diversity. Lastly, it was mentioned that there are limitations to exchange of genetic material between regions, as farmed fish species may escape their cages into the wild and subsequently result in genetic pollution of wild populations.

8.5 Enablers or levers for improving CLAGD

In the interviews, a range of enablers or levers for improving genetic diversity were addressed. For example, it was mentioned that there is room for improved knowledge exchange. It was mentioned that farmers are used as case studies to obtain scientific knowledge but that the obtained insights are not brought back to the farmer: farmers get their information from the industry, which may not always support farming system specific requirements. It was noted that more experiments need to be done to help farmers change their approach, and more collaboration in research across disciplines was mentioned to be useful. The positive role of collaborative pre-competitive research across private industry players (potentially in combination with the public sector and academia) was also emphasized. Also outside of research, collaboration was mentioned to provide opportunities. Sometimes one can have more impact if one joins groups outside of research, creating a more direct connection between stakeholders. Moreover, collaboration with local parties was mentioned as an enabler for enhancing genetic diversity. Stakeholders may collaborate with local parties to assess which breed is best suitable for the local environment and clear communication regarding why local breeds might be more suitable than the globally most-used breeds can help farmers make this choice. It was mentioned that plant breeders obtain their raw materials from (gene banks) across the world, hereby increasing the diversity in their product, when developing new varieties for different production environments in different regions. Also, more coordination across countries was mentioned to be beneficial, to reach beyond the competitiveness of countries, for example by having a (virtual) platform with a global outlook. Moreover, the current focus on regenerative agriculture allows for inclusion of biodiversity goals in the regenerative agriculture aims, although this inclusion of biodiversity is currently often lacking. Another enabler that was mentioned was more attention for (breeding for) interactions. In a monoculture plants must not compete with each other, and therefore one might want to combine complementary plant types that, for instance, have deep versus shallow rooting systems or are nitrogen-fixers versus nitrogen-takers, et cetera. In breeding, it was mentioned that it is generally assumed that the neighbouring plants are of the same genotype. Taking interactions into account in breeding programs could be beneficial. Moreover, it was mentioned that more research should be done regarding how DNA-level differences underlie different traits, to gain more insight into the genotype by environment interactions. Furthermore, it was mentioned that a possible approach is to aim for local production of protein instead of importing soy, for example. Moreover, instead of only using ryegrass in cattle systems, also herbs are mixed in and there is more attention for healthier and more resilient soils. Also mixed-species systems (cattle, sheep and poultry) and agroforestry systems were mentioned to have potential, contributing to better soil quality and a lower CO_2 footprint (see also **Section 7**). Such observations should be widely communicated to increase awareness and create impact in practice. Another approach that was mentioned was to raise consumer awareness and to gain more insight in consumer demands. More value needs to be created from diversity, for example through marketing of diversity. This also requires clearer definitions and interpretations of genetic diversity, not solely as an implicit part of the broader sustainability or regenerative agriculture marketing. Also, more interaction with society was mentioned as a possible lever. Many things are possible, but it is important to gain insight into the demands society has, both regarding the products themselves (e.g., Dutch consumers prefer brown eggs, while German consumers prefer white eggs, with latter actually having a lower carbon footprint) and what choices are considered responsible. Marketing can play a large role in increasing the attractiveness of products with increased genetic diversity associated with it. This is also important for technology development. It was mentioned that technology needs to be developed in a way that handles diversity and supports ecology. If society does not want more labour or to pay more for food, technology needs to be developed to make this possible. Moreover, a more tailor-made policy for farmers is needed, where we do not evaluate every farmer, or every production system, in the same way. Finally, it was mentioned that technologies should be judged on the product and not method, i.e., focus on whether the technology product has a positive effect, rather than how was this product made.

One of the main questions remains where diversity can be enhanced. It was mentioned that for genetic diversity, the most important part of the food chain where one can make changes is the primary production, and the subsequent chains can contribute to this by demanding responsibility from their primary producers . From the stakeholder interviews, it became clear that more support at the local level is needed for farmers to produce in a sustainable and resilient manner. Enhanced genetic diversity could play a large role in this, and companies support this. This also requires subsequent links in the supply chain to act, mainly through industry demanding responsibility from their primary producers. However, supply chains and consumers generally aim for an increased sustainability of production in the broad sense, with limited direct attention for genetic diversity. Increased genetic diversity is often not seen as a goal in itself. Moreover, to achieve increased genetic diversity, the earlier-mentioned lock ins (see **Section 8.4**) need to be addressed as well, for example requiring bakeries to adapt their baking processes to the quality or lower uniformity of the grain, instead of the other way around. Another remaining question that was raised was what the biodiversity is that one needs to get back at the local level: what indicators can we use and how do we measure this (see also **Section 2**)? What biodiversity supports the agricultural demands and how can agriculture maintain the role of food producer? The answer will likely be strongly dependent on the context and region.

9 CLAGD and food systems framework

Up to this point, we have discussed the evidence base for the relationships between, and interactions of, CLAGD and each of the four food system dimensions. Based on the results of the literature reviews and expert interviews, we here aim to provide directions for future systems-level thinking across the food system dimensions. In this section, we will 1) highlight a first set of key interventions that can be taken to enhance CLAGD within each of the four dimensions of the food system and discuss in short some key indicators to measure the effects of these interventions, 2) provide a conceptual framework that can be used to make explicit the trade-offs and synergies across these dimensions when implementing the key interventions identified to enhance CLAGD, and 3) show an example of implementing the framework. In future work, more interventions and concrete key indicators will be identified for the different food system dimensions. In general, however, it should be underlined that the scores and trade-offs in such a framework are dependent on scale, scope and context. It is obvious that trade-offs at the local level cannot always be generalised to the regional or global level. Moreover, global challenges in food systems are interdependent. This means that the different elements of food systems, like production systems including CLAGD, consumer behaviour, food security, climate change, natural conditions (i.e., the available natural resources) and socio-economic trends, interact with one another. Therefore, it is important to not seek possibilities for enhancing food security within a single subsystem without taking into account the effects of an intervention on other parts of the system, overlooking possible trade-offs. By mapping out the interactions between different subsystems, food-systems thinking and our proposed assessment framework can contribute to an integrated approach that makes use of solutions at different levels of scale.

9.1 Key interventions for enhancing CLAGD within each food system dimension

Even though the need for drastic change in food systems has become clear throughout this report, Conti et al. (2021) highlight that there is a certain resistance in food systems to change, resulting in lock-ins. Based on a systematic literature review, they mention six lock-ins relating to this resistance to food system change:

1. Technological persistence (i.e., dominant technologies persist at the expense of better alternatives because they are socially embedded; see also Bakker (2021) who shows this for the use of pesticides, and Peerlings and Polman (2008) who show this for agricultural nature management)
2. Misaligned institutional settings, policies and incentives
3. Attitudinal and cultural aversion to change
4. Political economy factors that skew the direction of change
5. Infrastructural rigidities
6. Research and innovation priorities practice and narratives misaligned to transformation

Based on the previous sections of this report and the FAO State of the World's Biodiversity report (FAO, 2019a), we distilled and summarized key interventions for enhancing CLAGD within each food system dimension, as shown in **Table 6**. These (and other) key interventions need to address the lock-ins to enhance the use of CLAGD in food systems.

For each of the four food system dimensions, key indicators for quantifying the effects of interventions to enhance CLAGD have to be identified, to examine their impact in practice. Although this is partly future work to complement, we highlight several example key indicators, for the four food system dimensions, in **Table 7**.

Table 6 *Overview of types of interventions for enhancing CLAGD in food systems, in different contexts. Based on FAO (2019a).*

Conservation and breeding	Production	Processing	Retail and consumption	Local cooperation and informal governance	National and global formal policy and regulation
Local/national community-based conservation programs, including establishment of ex situ gene banks	Encouragement for alternative practices from financial institutions	More advanced and flexible processing infrastructure in value chains	Demand for greater shelf diversity and healthy diets	Establish network of diverse coalitions	Support for breeding and conservation in developing countries
Establish global ex situ gene banks	Adapting sustainable management methods to local agroecological and socio-economic conditions	Local processing for short supply chains	Attach all ecosystem services values to product, including cultural origin	Raising farmer and industry awareness/support and engagement of science	Policy incentives for agro-ecology, regenerative agriculture, integrated farm/ecosystem management
Conservation of at risk breeds and varieties in native habitats	Integrated pest management	Experiment with new flavours from different varieties	Consumer awareness of the risk of monocrops and loss of CLAGD	Science-policy processes to help farmers with food transition	Adapted seed and breeding legislation
Global inventories of trends and risks	Nature protection: establish protected areas			Platforms and coordination for sharing genetic material	Acknowledgement and incentives for farmers that practice variation
Sustainable breeding programs	Reducing over fishing and by-catch				
Diversify breeding programs	Mixed farming systems, agroforestry and intercropping				
Breeding for crop interactions					

Table 7 *Overview of example key indicators for the four food system dimensions.*

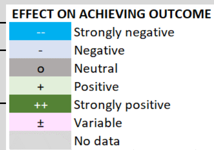
Food system dimension	Examples of key indicators
Safe and healthy diets	• Mineral and vitamin content and deficiencies • Levels of essential amino and fatty acids • Heavy metal concentrations • Levels of algal toxins • Pesticide residues • Plant toxin concentrations • Antibiotic residues • Concentrations of pathogens • Shelf life
Food security	• Productivity • Distribution • Allocation • Exchange • Affordability
Inclusiveness and equal benefits	• Household income • Business profit • Inclusive welfare • Access to insurance • Number of jobs • Transport costs • Capital investment costs • Land costs • Labour input costs • Processing costs • Waste
Sustainability and resilience	• Landscape diversity • Water quality • Soil structure • Natural biodiversity (e.g., species richness, abundance, diversity) • Disease resistance • Drought resistance • Heat resistance • Weed suppression

9.2 Conceptual framework for trade-offs and synergies across the food system dimensions

In **Table 8**, we show an example of a conceptual framework that could be used for making explicit the trade-offs and synergies of different potential interventions and their effects on different indicators for the four food system dimensions. Trade-offs are considered those interventions with negative and strongly negative effects, while synergies are those interventions with positive or strongly positive effects. These trade-offs and synergies can be visualised using colours and symbols (see legend of **Table 8**), to see at a glance what effect the interventions have on a specific food dimension indicator (e.g., overall positive, negative or neutral). In the conceptual framework in **Table 8**, the indicators for the different food system dimensions are aggregated, as our main aim is to show how such a conceptual framework could be of value. We intend to develop this framework into a more structured overview of interventions. This will also give an overview of the gaps in our knowledge (i.e., no data cells). The framework in **Table 8** is hierarchical, so that policy makers and practitioners are able to 'drill down' to a further level of detail, to explore the effects of more tangible (less aggregated) interventions on more specific indicators relevant to each food system dimension. **Table 9** shows the proposed level of detail we plan to further develop.

Table 8 *Conceptual framework for trade-offs and synergies across the food system dimensions.*

	Aggregated indicators for the four dimensions			
Aggregated interventions[1]	**Safe and healthy diets**	**Food security**	**Inclusiveness and equal benefits**	**Sustainability and resilience**
Conservation and breeding				
Production				
Processing				
Consumption				
Local cooperation and informal governance				
National and global formal policy and regulation				



[1] Only high-level typology of the interventions is shown here, these can be disaggregated into the interventions shown in Table 6.

Table 9 *A disaggregated version of Table 8, showing proposed management interventions. Each cell in this matrix links the effect of a specific intervention to the outcome of achieving an indicator for each food dimension. The effect will be described according to the legend in the centre of the matrix.*

		Aggregated indcators for the four dimensions[2]													
		Food security				Safe and healthy diets		Sustainability and resilience			Inclusiveness and equal benefits				
	Interventions1	Availability	Affordability	Stability/ reliability	Access	Nutrition	Safety	Ecosystem pressures	Ecosystem structure	Ecosystem function	Income	Expenses	Employment	Access to support	Cultural rights
Conservation & breeding	Establish community-based ex situ gene banks														
	Establish global ex situ gene banks														
	Conservation of at risk breeds and varieties in native habitats														
	Global inventory of breed/variety trends and risks														
	Breeding programs scoping broader variety of genotype														
	Sustainable breeding programs														
	More breeding for crop interactions														
Production	Financial institution incentives														
	Locally-contextualized agroecology														
	Integrated Pest Management														
	Nature protection: establish protected areas (EU policy)														
	Reducing overfishing and by-catch														
	Mixed farming systems, agro-forestry & intercropping														
Processin g	More flexible processing techniques in major value chains														
	Local processing														
	Experiment with new flavours from different varieties														
Consumption	Demand greater shelf diversity & healthy diets														
	Market ecosystem service values, incl. cultural origin														
	Consumer awareness of risks of monocrops & loss of CLAGD														
Local cooperation & informal governance	Establish network of diverse coalitions for increasing CLAGD														
	Raising farmer and industry awareness														
	Science-policy processes to help farmers on food transitions														
	Platforms and coordination for sharing genetic material														
National and global formal policy & regulation	Support for CLAGD breeding in developing countries														
	Support for artisanal fishing														
	Policy incentives and subsidies														
	Seed legislation														
	Acknowledgement of farmers that practice variation														

EFFECT ON ACHIEVING OUTCOME	
--	Strongly negative
-	Negative
o	Neutral
+	Positive
++	Strongly positive
±	Variable
	No data

[1] Only a list of potential interventions shown here; to be developed into a more structured typology.

[2] Only high-level typology of the four dimensions is shown here, these can be disaggregated into the indicators discussed earlier.

9.3 Example of implementing the framework

To highlight how our conceptual framework can contribute to making explicit the trade-offs and synergies of different potential interventions and their effects on different indicators, we here show an example for the reduction of pesticide use through increased use of CLAGD. This is a relevant issue, as several neonicotinoid insecticides are banned in the EU (European Commission, 2013). Assuming we want to achieve a reduction in pesticide use, there are different interventions that make use of enhanced CLAGD to compensate for the loss of pesticides. These interventions include, but are not limited to, an increased crop diversity and breeding for resistance.

In **Table 10**, we present a zoomed-in version of the framework, where we filled out these interventions and highlight some of the expected or hypothesised effects of these interventions. Based on the information from **Section 4**, increased crop diversity is expected to have positive effects on safe and healthy diets, as more biodiverse diets have been linked to improved nutritional value and health. Moreover, pesticide residues in food can negatively affect human health and therefore replacing pesticide use with natural alternative approaches, such as increased crop diversity, is expected to positively impact diet safety. In terms of food security, there may be both positive and negative effects of increasing crop diversity to reduce pesticide use. In the short-term, a reduction in pesticide use may result in losses of crops due to pests. However, when the crop diversity is increased, the benefits are that 1) more crop diversity can improve the resilience of the system towards pests (**Section 5**) and 2) some crops may be lost due to pests but other crops will not be affected, and therefore not the full harvest of a farm will be lost at once. The effects of increased crop diversity on inclusiveness and equal benefits are yet unclear and require more investigation in the future. In terms of sustainability and resilience, increased crop diversity can positively contribute to enhanced crop production, associated biodiversity (that is, the biodiversity of non-cultivated plants and animals), water quality, soil quality, and pest and disease control (Beillouin et al., 2021), and hereby to the sustainability and resilience of the food system (**Section 7**). Moreover, the reduction in pesticides itself can have positive consequences, as pesticides may destruct beneficial natural predators and parasites, result in the development and evolution of pesticide resistance in insect pests, plant pathogens and weeds, poison honeybees and wild bees that are viral for pollination, and may contaminate ground and surface water (Pimentel and Burgess, 2014). A reduction in pesticide use limits these effects.
In terms of breeding for resistance, the effects on safe and healthy diets are expected to be positive. Breeding for resistance results in an increased resistance to pests, and thereby to a reduction of pesticide residues in food, improving food safety. However, through breeding for resistance, biodiversity may not necessarily increase (or may even decrease if everyone uses a single resistant variety) and therefore the positive effects of improved nutritional value may not be applicable. In terms of food security, there will likely be fewer crop losses due to the resistance of the crops to pests. However, if at some point a new pest arises that the crop is not resistant to, the whole harvest may be lost, if still a single crop is used. The effects of breeding for resistance on inclusiveness and equal benefits are yet unclear and require more investigation in the future. In terms of resilience and sustainability, the same benefits of a reduction in pesticide use apply as discussed for increased crop diversity. However, it is important to keep in mind that pests may arise that the crop is not resistant to.

Table 10 *Example of implementation of framework for compensating for reduced pesticide use through CLAGD-related interventions.*

	Aggregated indicators for the four dimensions			
Interventions	**Safe and healthy diets**	**Food security**	**Inclusiveness and equal benefits**	**Sustainability and resilience**
Increased crop diversity	+	±		++
Breeding for resistance	+	±		++

10 Summary, conclusions and recommendations

With this report, we aimed to provide an overview of the current status and trends of use of crop, livestock and aquatic genetic diversity, in relation to food systems. The impact of decreased or enhanced use of crop, livestock and aquatic genetic diversity – within and across species and varieties – was discussed in relation to four food system dimensions: 1) safe and healthy diets, 2) food security, 3) inclusiveness and equal benefits, and 4) sustainability and resilience. Here, we summarize the main observations, from literature and expert or stakeholder interviews, and provide recommendations for future work in this area to increase the use and to make better use of genetic diversity in food systems.

10.1 Main observations

10.1.1 Trends in CLAGD

Even though the exact details may differ between crop, livestock and aquaculture systems, it is clear that the use of genetic diversity shows a declining trend, as a consequence of, among other things, specialisation and intensification, climate change and population growth. Clear consensus on how to measure and monitor crop, livestock and aquatic genetic diversity exactly is however lacking, and data collection and management are considered to be the main limiting factors in this. Adequate long term conservation of CLAGD is pivotal, but major gaps remain, despite increasing conservation efforts.

10.1.2 Consequences of declining CLAGD

The decline in CLAGD can pose serious threats, including increased disease and pest vulnerability, reduced resilience (for example regarding drought and climate change), increased economic vulnerability, loss of local knowledge and culture, limited food security, and insufficient diversity in breeding animals or crops for the development of improved or new varieties or breeds for future systems or circumstances.

10.1.3 CLAGD and the four food system dimensions

Decreased or increased CLAGD may (indirectly) affect all four food system dimensions. Regarding healthy diets, biodiverse diets (in other words, diets that include different food groups, categories or types) can have positive effects on human health, for example through lowering the probability of obtaining chronic non-communicable diseases, and can contribute to achieving recommended daily intakes. Regarding safe diets, there are both positive and adverse effects of increased biodiversity, as, for example, increased biodiversity leads to increased resilience to pests and animal diseases and therefore less risk of chemical residues, yet at the same time increased biodiversity in grasslands can result in increased exposure to plant toxins. Regarding food security, increased genetic diversity can contribute to the prevention of disasters like widespread plant diseases and consequent losses. Regarding inclusiveness and equal benefits, the relationship with CLAGD can work in both directions, with increased CLAGD potentially contributing to achieving inclusiveness and equal benefits, and with increased equal benefits potentially aiding in conservation of on-farm CLAGD. Regarding sustainability and resilience, there is a lot of evidence for positive effects of crop diversification on crop ecosystem services, yet there are hurdles for more widespread implementation of crop diversification, including gaps in biological knowledge, as well as socio-economic and technical issues. Moreover, there appear to be beneficial effects of multispecies systems in livestock and aquaculture, as well as of crop-livestock mixed systems, but more spatially large-scaled and longitudinal studies are needed to address the unknowns. Overall, these dimensions are strongly linked, and so is the role of CLAGD in these systems. For example, by promoting sustainable and resilient food systems through increased biodiversity use, food security and inclusiveness can be improved as well.

10.2 Recommendations for policies and future work

In this section, we will highlight some key topics for future research and for policies to address, based on the main conclusions from the literature study and the expert and stakeholder interviews. We have grouped these recommendations by topic, with some recommendations being more general and others being quite specific. Different interventions may interact, and therefore it is recommended that close attention is paid to the effects of these interventions on other components of biodiversity or food systems as well, to determine whether there are no negative or unwanted side effects of these interventions.

10.2.1 Data and monitoring

Main challenges in monitoring of the current use of CLAGD are the lack of (standardised) measurement methods and lacking data. For example, (regularly updated) data are lacking on the size and structure of livestock breed populations, as well as for inland fisheries. In this respect, we recommend the following further actions:

- To (develop and) implement standardised guidelines on how to better monitor and implement CLAGD, focussing not only on conservation but also on use in the field
    - Also focussing on within-species (crops and aquaculture) or within-breed (livestock) genetic diversity
- To (develop and) implement standardised gene bank documentation, to allow better monitoring of ex situ conservation

10.2.2 Research

Even though much research is being performed in the context of biodiversity and food systems, there are still some limitations to the current research, which can be addressed in future research. We recommend the following further actions for future research:

- Research should aim to address the problem as a whole, instead of separately studying subcomponents of the issue
    - Moreover, research should look into combining different measures, for example studying combinations of different crop diversification approaches (see **Table 3**), or examining possibilities for breeding for interactions
- Research should also focus on long term effects and large spatial scales to examine the effects in practice, as currently research often takes place in controlled environments that do not capture the agricultural complexity
    - To achieve this, more collaboration is needed between research institutes (as single research groups can often not afford these types of studies), for example at EU level
- Researchers should collaborate more with local parties, to also study genotype by environment interactions and to bring the obtained knowledge back to the farmers

10.2.3 Societal awareness and market incentives

To achieve increases in CLAGD in food systems, awareness of the issue is needed, as well as incentives to take action. It was mentioned in the expert and stakeholder interviews that stakeholders respond to retail, consumer and/or societal demands (for example from NGOs), but that large incentives for increased biodiversity from consumers are currently lacking. In this respect, we recommend the following further actions:

- To increase consumer awareness for the importance of CLAGD in food systems and to bring across the message that biodiversity is a shared responsibility
    - Also aim to have consumers include diversity in their behaviour, i.e., to pay more for biodiversity-inclusive products (that for example indicate so on their packaging)
- To promote diversity as an attribute of products, to increase the demand for local varieties or products from local (at-risk) breeds
    - This can for example be achieved through the use of food-based dietary guidelines

10.2.4 Technologies

Several technological difficulties are currently faced in relation to transitioning towards more biodiverse food systems. We recommend the following main action to be taken:

- More attention for and investment in technologies that can handle diversity, for example harvesting machines that can handle crops of different heights

10.2.5 Public policies, regulations and financial incentives

Changes in policies and regulations, as well as financial incentives, can greatly benefit enhanced use of CLAGD. In this respect, we recommend the following actions:

- Develop and implement regulations and incentives to maintain and to make available a broader range of species and quality varieties or breeds to producers and value chains
    - Also increase coordination, for example through a (virtual) platform with a global outlook, to reach beyond the competitiveness of different countries
- Develop a more tailor-made policy for farmers, where every farmer, or every production system, can be valued differently
- Include biodiversity goals explicitly in the current focus on regenerative agriculture
- Provide financial incentives (like taxes or subsidies) for more diverse systems

10.2.6 Commercial parties

Commercial parties, such as breeding companies, food processors and retailers, can actively contribute to enhancing the use of CLAGD in food systems. We recommend the following associated actions:

- Breeding companies could focus more on diversity in selection schemes, invest in a wider product portfolio, and also contribute to long term conservation of genetic diversity in crops, livestock and aquatic species
- Subsequent chains in the food system should also adapt to diversity (for example millers and bakeries accepting mixed cereals)

References

Ahlemeyer, J., Snowdon, R.J., Ordon, F. and Friedt, W. (2006). Agrodiversity: genetic diversity in crops and cropping systems. In Benckiser, G. and Schnell, S. (Eds.), Biodiversity in Agricultural Production Systems. Taylor & Francis Group, Boca Raton. pp. 21-40

Allen, T., Prosperi, P., Cogill, B. and Flichman, G. (2014). Agricultural biodiversity, social–ecological systems and sustainable diets. Proceedings of the Nutrition Society, 73(4), 498-508. doi:10.1017/S002966511400069X

Appleby, P.N., Crowe, F.L., Bradbury, K.E., Travis, R.C. and Key, T.J. (2016). Mortality in vegetarians and comparable nonvegetarians in the United Kingdom. The American Journal of Clinical Nutrition, 103(1), 218-230. doi:10.3945/ajcn.115.119461

Argumedo, A., Song, Y., Khoury, C.K., Hunter, D., Dempewolf, H., Guarino, L. and de Haan, S. (2021). Biocultural diversity for food system transformation under global environmental change. Frontiers in Sustainable Food Systems, 5, 685299. doi:10.3389/fsufs.2021.685299

Bakker, L. (2021). Insects and insecticides in agricultural landscapes: socio-ecological challenges and patterns. Dissertation, Wageningen University & Research, Wageningen. doi:10.18174/538522

Barnes, K., Collins, T., Dion, S., Reynolds, H., Riess, S., Stanzyk, A., Wolfe, A., Lonergan, S., Boettcher, P., Charrondiere, U.R. and Stadlmayr, B. (2012). Importance of cattle biodiversity and its influence on the nutrient composition of beef. Animal Frontiers, 2(4), 54-60. doi:10.2527/af.2012-0062

Beillouin, D., Ben-Ari, T. and Makowski, D. (2019). A dataset of meta-analyses on crop diversification at the global scale. Data in Brief, 24. doi:10.1016/j.dib.2019.103898

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V. and Makowski, D. (2021). Positive but variable effects of crop diversification on biodiversity and ecosystem services. Global Change Biology, 27(19), 4697-4710. doi:10.1111/gcb.15747

Beketov, M.A., Kefford, B.J., Schäfer, R.B. and Liess, M. (2013). Pesticides reduce regional biodiversity of stream invertebrates. Proceedings of the National Academy of Sciences, 110(27), 11039-11043. doi:10.1073/pnas.1305618110

Bernhardt, J.R. and O'Connor, M.I. (2021). Aquatic biodiversity enhances multiple nutritional benefits to humans. Proceedings of the National Academy of Sciences, 118(15), e1917487118. doi:10.1073/pnas.1917487118

Bobbo, T., Penasa, M. and Cassandro, M. (2020). Genetic parameters of bovine milk fatty acid profile, yield, composition, total and differential somatic cell count. Animals, 10, 2406. doi:10.3390/ani10122406

Borg, J., Kiær, L.P., Lecarpentier, C., Goldringer, I., Gauffreteau, A., Saint-Jean, S., Barot, S. and Enjalbert, J. (2018). Unfolding the potential of wheat cultivar mixtures: A meta-analysis perspective and identification of knowledge gaps. Field Crops Research, 221, 298-313. doi:10.1016/j.fcr.2017.09.006

Brooker, R.W., Bennett, A.E., Cong, W.F., Daniell, T.J., George, T.S., Hallett, P.D., Hawes, C., Iannetta, P.P.M., Jones, H.G., Karley, A.J., Li, L., McKenzie, B.M., Pakeman, R.J., Paterson, E., Schöb, C., Shen, J., Squire, G., Watson, C.A., Zhang, C., Zhang, F., Zhang, J. and White, P.J. (2015). Improving intercropping: A synthesis of research in agronomy, plant physiology and ecology. New Phytologist, 206(1), 107-117. doi:10.1111/nph.13132

Brouwer, I.D., McDermott, J. and Ruben, R. (2020). Food systems everywhere: Improving relevance in practice. Global Food Security, 26. doi:10.1016/j.gfs.2020.100398

Conti, C., Zanello, G. and Hall, A. (2021). Why are agri-food systems resistant to new directions of change? A systematic review. Global Food Security, 31. doi:10.1016/j.gfs.2021.100576

Convention on Biological Diversity. (2010). A new era of living in harmony with nature is born at the Nagoya Biodiversity Summit [Press release]. Retrieved from https://www.cbd.int/doc/press/2010/pr-2010-10-29-cop-10-en.pdf

Convention on Biological Diversity. (2021). Decisions adopted by the Conference of the Parties to the Convention on Biological Diversity at its Tenth Meeting. Retrieved from: https://www.cbd.int/doc/decisions/cop-10/full/cop-10-dec-en.pdf

Dulloo, E.M., Bissessur, P. and Rana, J. (2021). Monitoring plant genetic resources for food and agriculture. In: Dulloo, E.M. (ed.) Plant genetic resources: A review of current research and future needs. Burleigh Dodds Science Publishing, p. 55-80. ISBN: 978-1-78676-451-5

Dumont, B., Puillet, L., Martin, G., Savietto, D., Aubin, J., Ingrand, S., Niderkorn, V., Steinmetz, L. and Thomas, M. (2020). Incorporating diversity into animal production systems can increase their performance and strengthen their resilience. Frontiers in Sustainable Food Systems, 4. doi:10.3389/fsufs.2020.00109

Ebert, A.W. (2014). Potential of underutilized traditional vegetables and legume crops to contribute to food and nutritional security, income and more sustainable production systems. Sustainability, 6(1), 319-335. doi:10.3390/su6010319

Ebert, A.W. (2020). The role of vegetable genetic resources in nutrition security and vegetable breeding. Plants (Basel), 9(6). doi:10.3390/plants9060736

Ericksen, P.J. (2008). Conceptualizing food systems for global environmental change research. Global environmental change, 18(1), pp.234-245. doi:10.1016/j.gloenvcha.2007.09.002

European Commission. (2013). Bees & Pesticides: Commission to proceed with plan to better protect bees. Press release, Brussels, 29 April 2013. Retrieved from: https://ec.europa.eu/commission/presscorner/detail/en/IP_13_379

European Commission. (2019). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal. Available at: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF (last accessed on March 3, 2022)

Evers, J.B., Van Der Werf, W., Stomph, T.J., Bastiaans, L. and Anten, N.P.R. (2019). Understanding and optimizing species mixtures using functional-structural plant modelling. Journal of Experimental Botany, 70(9), 2381-2388. doi:10.1093/jxb/ery288

Fan, S. and Swinnen, J. (2020). Reshaping food systems: The imperative of inclusion. In: 2020 Global Food Policy Report. Washington, DC: International Food Policy Research Institute (IFPRI). pp.6-13. doi:10.2499/9780896293670_01

FAO. (1996). Rome Declaration on World Food Security. Retrieved from: https://www.fao.org/3/w3613e/w3613e00.htm

FAO. (1997). The State of the World's Plant Genetic Resources for Food and Agriculture. Retrieved from: http://www.fao.org/3/a-w7324e.pdf

FAO. (2010). The Second Report on the State of the World's Plant Genetic Resources for Food and Agriculture. Retrieved from: https://www.fao.org/docrep/013/i1500e/i1500e.pdf

FAO. (2015). The Second Report on the State of the World's Animal Genetic Resources for Food and Agriculture. Retrieved from: https://www.fao.org/3/i4787e/i4787e.pdf

FAO. (2017). Nutrition-sensitive agriculture and food systems in practice - Options for intervention. Retrieved from: https://www.fao.org/3/i7848e/i7848e.pdf

FAO. (2018a). The State of World Fisheries and Aquaculture 2018 – Meeting the sustainable development goals. Retrieved from: https://www.fao.org/3/i9540en/i9540en.pdf

FAO. (2018b). Sustainable food systems - concept and framework. Retrieved from: https://www.fao.org/3/ca2079en/CA2079EN.pdf

FAO. (2019a). The State of the World's Biodiversity for Food and Agriculture, J. Bélanger & D. Pilling (eds.). FAO Commission on Genetic Resources for Food and Agriculture Assessments. Rome. 572 pp. Retrieved from: http://www.fao.org/3/CA3129EN/CA3129EN.pdf

FAO. (2019b). The State of the World's Aquatic Genetic Resources for Food and Agriculture. FAO Commission on Genetic Resources for Food and Agriculture assessments. Retrieved from: https://www.fao.org/3/ca5345en/ca5345en.pdf

FAO. (2021a). Commission on Genetic Resources for Food and Agriculture. Retrieved from: https://www.fao.org/cgrfa/overview/history/en/ (last accessed on March 3, 2022)

FAO. (2021b). Sustainable development goals. Retrieved from: https://www.fao.org/sustainable-development-goals/goals/goal-2/en/ (last accessed on March 3, 2022)

FAO. (2021c). The State of Food Security and Nutrition in the World – Transforming Food Systems 2021. Retrieved from: https://www.fao.org/3/cb4474en/cb4474en.pdf

FAO. (2022). Gateway to dairy production and products. Retrieved from: https://www.fao.org/dairy-production-products/production/dairy-animals/en/ (last accessed on June 26, 2022)

Fatima, A., Farid, M., Safdar, K., Fayyaz, A., Ali, S. M., Adnan, S., Nawaz, M., Munir, H., Raza, N. and Zubair, M. (2020). Loss of Agro-Biodiversity and Productivity Due to Climate Change in Continent Asia: A Review. In: Hasanuzzaman, M. (Ed.), Plant Ecophysiology and Adaptation under Climate Change: Mechanisms and Perspectives I: General Consequences and Plant Responses (pp. 51-71). Springer, Singapore. doi:10.1007/978-981-15-2156-0_2

Franzluebbers, A.J. and Stuedemann, J.A. (2010). Surface soil changes during twelve years of pasture management in the southern Piedmont USA. Soil Science Society of America Journal, 74(6), 2131-2141. doi:10.2136/sssaj2010.0034

Fresco, L.O., Ruben, R. and Herens, M. (2017). Challenges and perspectives for supporting sustainable and inclusive food systems. GREAT Insights Magazine, 6(4). September/October 2017.

Frison, E.A., Cherfas, J. and Hodgkin, T. (2011). Agricultural Biodiversity Is Essential for a Sustainable Improvement in Food and Nutrition Security. Sustainability, 3(1), 238-253. doi:10.3390/su3010238

Fuller, H. (2022). Bananas: a story of clones and colonization. Available at: https://groundedgrub.com/articles/bananas (last accessed on March 3, 2022)

Gaupp, F., Ruggeri Laderchi, C., Lotze-Campen, H., DeClerck, F., Bodirsky, B. L., Lowder, S., Popp, A., Kanbur, R., Edenhofer, O., Nugent, R., Fanzo, J., Dietz, S., Nordhagen, S. and Fan, S. (2021). Food system development pathways for healthy, nature-positive and inclusive food systems. Nature Food, 2(12), 928-934. doi:10.1038/s43016-021-00421-7

Gerullis, M.K., Heckelei, T. and Rasch, S. (2021). Toward understanding the governance of varietal and genetic diversity. Ecology and Society, 26(2). doi:10.5751/ES-12333-260228

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. and Toulmin, C. (2010). Food security: the challenge of feeding 9 billion people. Science, 327 (5967) doi:10.1126/science.1185383

Gonzalez Fischer, C. and Garnett, T. (2016). Plates, pyramids, planet - Developments in national healthy and sustainable dietary guidelines: a state of play assessment. Rome, FAO, and Oxford, UK, Food Climate Research Network. Retrieved from: http://www.fao.org/3/a-i5640e.pdf

Gregory, P.J., Azam-Ali, S. and Azam-Ali, S. (2018). Crops for the Future (CFF).

Gu, C., Bastiaans, L., Anten, N.P.R., Makowski, D. and van der Werf, W. (2021). Annual intercropping suppresses weeds: A meta-analysis. Agriculture, Ecosystems and Environment, 322. doi:10.1016/j.agee.2021.107658

Hammen, V.C. and Settele, J. (2011). Biodiversity and the loss of biodiversity affecting human health. In: Nriagu, J.O. (Ed.), Encyclopedia of Environmental Health. pp. 353-362. doi:10.1016/B978-0-444-52272-6.00655-3

Hoban, S., Bruford, M., D'Urban Jackson, J., Lopes-Fernandes, M., Heuertz, M., Hohenlohe, P.A., Paz-Vinas, I., Sjögren-Gulve, P., Segelbacher, G., Vernesi, C., Aitken, S., Bertola, L.D., Bloomer, P., Breed, M., Rodríguez-Correa, H., Funk, W.C., Grueber, C.E., Hunter, M.E., Jaffe, R., Liggins, L., Mergeay, J., Moharrek, F., O'Brien, D., Ogden, R., Palma-Silva, C., Pierson, J., Ramakrishnan, U., Simo-Droissart, M., Tani, N., Waits, L. and Laikre, L. (2020). Genetic diversity targets and indicators in the CBD post-2020 Global Biodiversity Framework must be improved. (2020) Biological Conservation, 248, 108654. doi:10.1016/j.biocon.2020.108654

Hoogenboom, L.A.P., Mulder, P.P.J., Zeilmaker, M.J., van den Top, H.J., Remmelink, G.J., Brandon, E.F.A., Klijnstra, M., Meijer, G.A.L., Schothorst, R. and Van Egmond, H.P. (2011). Carry-over of pyrrolizidine alkaloids from feed to milk in dairy cows. Food Additives & Contaminants: Part A, 28(3), 359-372. doi:10.1080/19440049.2010.547521

Hough, R.L. (2014). Biodiversity and human health: evidence for causality? Biodiversity and Conservation, 23(2), 267-288. doi:10.1007/s10531-013-0614-1

Hughes, A.R., Inouye, B.D., Johnson, M.T., Underwood, N. and Vellend, M. (2008). Ecological consequences of genetic diversity. Ecology Letters, 11(6), 609-623. doi:10.1111/j.1461-0248.2008.01179.x

IFAD. (2021). How to do: Promote neglected and underutilized species for domestic markets. Nutrition-sensitive Agriculture – Note no. 3. Retrieved from: https://www.ifad.org/documents/38714170/43559125/HTDN_NUS_3.pdf/297d93eb-330b-19a1-4804-c31d49e9fd37?t=1629384619783

IFPRI (International Food Policy Research Institute). (2020). 2020 Global Food Policy Report: Building Inclusive Food Systems. Washington, DC: International Food Policy Research Institute. doi:10.2499/9780896293670

IPBES. (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E.S. Brondízio, H.T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K.A. Brauman, S.H.M. Butchart, K.M.A. Chan, L.A. Garibaldi, K. Ichii, J. Liu, S.M. Subramanian, G.F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y.J. Shin, I.J. Visseren-Hamakers, K.J. Willis, and C.N. Zayas (eds.). IPBES secretariat, Bonn, Germany. 56 pages. doi:10.5281/zenodo.3553579

IPK (Leibniz Institute of Plant Genetics and Crop Plant Research). (2021). Mansfeld's World Database of Agriculture and Horticultural Crops. Available at: http://mansfeld.ipk-gatersleben.de/apex/f?p=185:3 (last accessed on November 8, 2021)

Johns, T. and Eyzaguirre, P.B. (2006). Linking biodiversity, diet and health in policy and practice. Proceedings of the Nutrition Society, 65(2), 182-189. doi:10.1079/PNS2006494

Jones, A.D. (2017). Critical review of the emerging research evidence on agricultural biodiversity, diet diversity, and nutritional status in low- and middle-income countries. Nutrition Reviews, 75(10), 769-782. doi:10.1093/nutrit/nux040

Jones, M.S., Fu, Z., Reganold, J.P., Karp, D.S., Besser, T.E., Tylianakis, J.M. and Snyder, W.E. (2019). Organic farming promotes biotic resistance to foodborne human pathogens. Journal of Applied Ecology, 56(5), 1117-1127. doi:10.1111/1365-2664.13365

Kennedy, G., Islam, O., Eyzaguirre, P. and Kennedy, S. (2005). Field testing of plant genetic diversity indicators for nutrition surveys: rice-based diet of rural Bangladesh as a model. Journal of Food Composition and Analysis, 18(4), 255-268. doi:10.1016/j.jfca.2004.10.002

Kennedy, G., Stoian, D., Hunter, D., Kikulwe, E., Termote, C., Alders, R., Burlingame, B., Jamnadass, R., McMullin, S. and Thilsted, S. (2017). Food biodiversity for healthy, diverse diets. In: Bioversity International (Ed.), Mainstreaming Agrobiodiversity in Sustainable Food Systems - Scientific Foundations for an Agrobiodiversity Index Bioversity International. pp. 23-52. ISBN13:978-92-9255-070-7

Key, T.J., Papier, K. and Tong, T.Y.N. (2021). Plant-based diets and long-term health: findings from the EPIC-Oxford study. Proceedings of the Nutrition Society, 1-9. doi:10.1017/S0029665121003748

Khoury, C.K., Amariles, D., Soto, J.S., Diaz, M.V., Sotelo, S., Sosa, C.C., Ramírez-Villegas, J., Achicanoy, H.A., Velásquez-Tibatá, J., Guarino, L., León, B., Navarro-Racines, C., Castañeda-Álvarez, N.P., Dempewolf, H., Wiersema, J.H. and Jarvis, A. (2019). Comprehensiveness of conservation of useful wild plants: An operational indicator for biodiversity and sustainable development targets. Ecological Indicators, 98, 420-429. doi:10.1016/j.ecolind.2018.11.016

Khoury, C.K., Bjorkman, A.D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A., Rieseberg, L.H. and Struik, P.C. (2014). Increasing homogeneity in global food supplies and the implications for food security. Proceedings of the National Academy of Sciences, 111(11), 4001-4006. doi:10.1073/pnas.1313490111

Khoury, C.K., Carver, D., Greene, S.L., Williams, K.A., Achicanoy, H.A., Schori, M., León, B., Wiersema, J.H. and Frances, A. (2020). Crop wild relatives of the United States require urgent conservation action. Proceedings of the National Academy of Sciences, 117(52), 33351-33357. doi:10.1073/pnas.2007029117

Koning, N.B.J., Van Ittersum, M.K., Becx, G.A., Van Boekel, M.A.J.S., Brandenburg, W.A., Van Den Broek, J.A., Goudriaan, J., Van Hofwegen, G., Jongeneel, R.A., Schiere, J.B. and Smies, M. (2008). Long-term global availability of food: continued abundance or new scarcity?, NJAS - Wageningen Journal of Life Sciences, 55:3, 229-292, doi:10.1016/S1573-5214(08)80001-2

Lemaire, G., Franzluebbers, A., Carvalho, P.C.d.F. and Dedieu, B. (2014). Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. Agriculture, Ecosystems & Environment, 190, 4-8. doi:10.1016/j.agee.2013.08.009

Li, C., Hoffland, E., Kuyper, T.W., Yu, Y., Zhang, C., Li, H., Zhang, F. and van der Werf, W. (2020). Syndromes of production in intercropping impact yield gains. Nature Plants, 6(6), 653-660. doi:10.1038/s41477-020-0680-9

MacEvilly, C. (2003). Cereals | Contribution to the diet. In: Cabellero, B. (ed), Encyclopedia of Food Sciences and Nutrition (second edition), pp. 1008-1014. doi:10.1016/B0-12-227055-X/00186-3Magne, M.A., Thénard, V. and Mihout, S. (2016). Initial insights on the performances and management of dairy cattle herds combining two breeds with contrasting features. Animal, 10(5), 892-901. doi:10.1017/S1751731115002840

Maillard, J.-C. and Gonzalez, J.-P. (2016). Biodiversity and Emerging Diseases. Annals of the New York Academy of Sciences, 1081, 1-16. doi:10.1196/annals.1373.001

Manel, S., Guerin, P.E., Mouillot, D., Blanchet, S., Velez, L., Albouy, C. and Pellissier, L. (2020). Global determinants of freshwater and marine fish genetic diversity. Nature Communications, 11(1), 692. doi:10.1038/s41467-020-14409-7

Mathur, P.N. (2011). Assessing the threat of genetic erosion. In: Guarino, L., RamanathaRao, V. and Goldberg, E. (Eds.), Collecting plant genetic diversity technical guidelines—2011 update. Rome: Biodiversity International.

Ministry of Agriculture, Nature and Food Quality. (2019). Plan of action - The Dutch government's plan to support the transition to circular agriculture. Retrieved from: https://www.government.nl/binaries/government/documents/policy-notes/2019/11/30/plan-of-action---supporting-transition-to-circular-agriculture/Plan+of+action+-+supporting+transition+to+circular+agriculture.pdf

Muranaka, S., Shono, M., Myoda, T., Takeuchi, J., Franco, J., Nakazawa, Y., Boukar, O. and Takagi, H. (2016). Genetic diversity of physical, nutritional and functional properties of cowpea grain and relationships among the traits. Plant Genetic Resources, 14(1), 67-76. doi:10.1017/S147926211500009X

Néstor, M.C. and Mariana, C. (2019). Impact of Pharmaceutical Waste on Biodiversity. In: Gómez-Oliván, L.M. (Ed.), Ecopharmacovigilance: Multidisciplinary Approaches to Environmental Safety of Medicines. Springer International Publishing. pp. 235-253. doi:10.1007/978-3-319-73476-7

NewForesight and Commonland. (2017). New Horizons for the Transitioning of our Food System: Connecting Ecosystems, Value Chains and Consumers. Discussion paper by NewForesight and Commonland with contributions from The Boston Consulting Group. Retrieved from: https://www.commonland.com/wp-content/uploads/2019/09/Newhorizonsfortransitioningourfoodsystemdiscussionpaper3_548469743.pdf

OP2B. (2021). One Planet Business for Biodiversity. Retrieved from: https://op2b.org/ (last accessed on March 3, 2022)

Ostfeld, R.S. and Keesing, F. (2013). Biodiversity and Human Health. In: Levin, S.A. (Ed.), Encyclopedia of Biodiversity (Second Edition). Waltham: Academic Press. pp. 357-372. doi:10.1016/B978-0-12-384719-5.00332-4

Our World in Data. (2021). Meat production by animal. Retrieved from: https://ourworldindata.org/meat-production#meat-production-by-animal (last accessed on November 8, 2021)

Palma-Granados, P., Haro, A., Lara, L., Aguilera, J.F., Nieto, R. and Seiquer, I. (2018). Differences on meat colour and composition between 'Landrace x Large White' and 'Iberian' pigs under identical nutritional and management conditions. Animal Production Science, 58, 2132-2142. doi:10.1071/AN16375
Peerlings, J. and Polman, N. (2008). Agri-environmental contracting of Dutch dairy farms: The role of manure policies and the occurrence of lock-in. European Review of Agricultural Economics, 35(2), 167-191. doi:10.1093/erae/jbn022
Penafiel, D., Lachat, C., Espinel, R., Van Damme, P. and Kolsteren, P. (2011). A Systematic Review on the Contributions of Edible Plant and Animal Biodiversity to Human Diets. EcoHealth, 8(3), 381-399. doi:10.1007/s10393-011-0700-3
Pimentel, D. and Burgess, M. (2014). Environmental and economic costs of the application of pesticides primarily in the United States. In: Pimentel, D. and Peshin, R. (eds), Integrated Pest Management, Pesticide Problems, Vol. 3 (eds), pp. 47-71.
Powell, B., Thilsted, S.H., Ickowitz, A., Termote, C., Sunderland, T. and Herforth, A. (2015). Improving diets with wild and cultivated biodiversity from across the landscape. Food Security, 7(3), 535-554. doi:10.1007/s12571-015-0466-5
Rana, R.B., Garforth, C., Sthapit, B. and Jarvis, D. (2007). Influence of socio-economic and cultural factors in rice varietal diversity management on-farm in Nepal. Agriculture and Human Values, 24:461-472. doi:10.1007/s10460-007-9082-0
Reiss, E.R. and Drinkwater, L.E. (2018). Cultivar mixtures: A meta-analysis of the effect of intraspecific diversity on crop yield: A. Ecological Applications, 28(1), 62-77. doi:10.1002/eap.1629
RGB (Royal Botanic Gardens) Kew. (2016). State of the World's Plants. Retrieved from: https://stateoftheworldsplants.org/2016/report/sotwp_2016.pdf
Sabaté, J. (2003). The contribution of vegetarian diets to health and disease: a paradigm shift? The American Journal of Clinical Nutrition, 78(suppl):502S-507S. doi:10.1093/ajcn/78.3.502S
Schmeller, D.S., Courchamp, F. and Killeen, G. (2020). Biodiversity loss, emerging pathogens and human health risks. Biodiversity and Conservation, 29(11), 3095-3102. doi:10.1007/s10531-020-02021-6
Smale, M., Bellon, M.R., Jarvis, D. and Sthapit, B. (2004). Economic concepts for designing policies to conserve crop genetic resources on farms. Genetic Resources and Crop Evolution, 51:121-135. doi:10.1023/B:GRES.0000020678.82581.76
Tang, X., Zhang, C., Yu, Y., Shen, J., van der Werf, W. and Zhang, F. (2021). Intercropping legumes and cereals increases phosphorus use efficiency; a meta-analysis. Plant and Soil, 460(1-2), 89-104. doi:10.1007/s11104-020-04768-x
Technology for Ecology. (2021). Synergia. Retrieved from: https://technology4ecology.org/synergia/ (last accessed on March 3, 2022)
Thomas, M., Pasquet, A., Aubin, J., Nahon, S. and Lecocq, T. (2021) When more is more: taking advantage of species diversity to move towards sustainable aquaculture. Biological Reviews, 96, 767-784. doi:10.1111/brv.12677
Three Top Sectors for enterprise and innovation in the Netherlands: Agri & Food, Horticulture & Staring Materials, and High-Tech Systems & Materials. (2017). 8 game changers for sustainable production of safe and healthy food. Retrieved from: https://topsectoragrifood.nl/wp-content/uploads/2018/01/NWA-brochure-Sustainable-production-of-safe-and-healthy-food-final.pdf
Tobin, D., Jones, K. and Thiede, B.C. (2019). Does crop diversity at the village level influence child nutrition security? Evidence from 11 sub-Saharan African countries. Population and Environment, 41(2), 74-97. doi:10.1007/s11111-019-00327-4
Tripathi, S.D. and Sharma, B.K. (2001) Integrated fish-horticulture farming in India. In: FAO (ed.), Integrated agriculture-aquaculture - a primer.
United Nations. (2015). Transforming our world: the 2030 agenda for sustainable development.
United Nations. (2021). Department of Economic and Social Affairs – Sustainable development. Available at: https://sdgs.un.org/goals/goal2

University at Buffalo. (2022). Cultivating food equity. Available at: https://www.buffalo.edu/globalhealthequity/global-projects/foodequity.html (last accessed on March 3, 2022).
van Berkum, S., Dengerink, J., & Ruben, R. (2018). The food systems approach: sustainable solutions for a sufficient supply of healthy food. doi:10.18174/451505
van de Wouw, M., van Hintum, T., Kik, C., van Treuren, R. and Visser, B. (2010). Genetic diversity trends in twentieth century crop cultivars: a meta analysis. Theoretical and Applied Genetics, 120(6), 1241-1252. doi:10.1007/s00122-009-1252-6
van Raamsdonk, L.W.D., Mulder, P. and Uiterwijk, M. (2010). Identification tools as part of Feedsafety research: the case of ragwort. In: Tools for Identifying Biodiversity. Universitá di Trieste, Venice. pp. 213-216. ISBN:9788883032950
van Raamsdonk, L.W.D., Ozinga, W.A., Hoogenboom, L.A.P., Mulder, P.P.J., Mol, J.G.J., Groot, M.J., van der Fels-Klerx, H.J. and de Nijs, M. (2015). Exposure assessment of cattle via roughages to plants producing compounds of concern. Food Chemistry, 189, 27-37. doi:10.1016/j.foodchem.2015.02.050
Verdonschot, P.F.M., Spears, B.M., Feld, C.K., Brucet, S., Keizer-Vlek, H., Borja, A., Elliott, M., Kernan, M. and Johnson, R.K. (2013). A comparative review of recovery processes in rivers, lakes, estuarine and coastal waters. Hydrobiologia, 704(1), 453-474. doi:10.1007/s10750-012-1294-7
Wageningen University & Research. (2021a). Food systems. Retrieved from: https://www.wur.nl/en/Research-Results/Themes/From-hunger-to-food-security/Food-Systems.htm (last accessed on March 3, 2022)
Wageningen University & Research. (2021b). Strip cropping. Retrieved from: https://www.wur.nl/en/project/strip-cropping.htm (last accessed on March 3, 2022)
Wageningen University & Research. (2021c). Virtual Plant Network Wageningen. Retrieved from https://www.wur.nl/en/research-results/projects-and-programmes/virtual-plant-network-wageningen.htm (last accessed on March 3, 2022)
Wagner, K.H. and Brath, H. (2012). A global view on the development of non communicable diseases. Preventive Medicine, 54 Suppl, S38-41. doi:10.1016/j.ypmed.2011.11.012
Wahab, M.A., Kadir, A., Milstein, A. and Kunda, M. (2011). Manipulation of species combination for enhancing fish production in polyculture systems involving major carps and small indigenous fish species. Aquaculture, 321(3-4), 289-297. doi:10.1016/j.aquaculture.2011.09.020
World Economic Forum. (2017). Shaping the Future of Global Food Systems: A Scenarios Analysis. A report by the World Economic Forum's System Initiative on Shaping the Future of Food Security and Agriculture, prepared in collaboration with Deloitte Consulting LLP. Retrieved from: https://www3.weforum.org/docs/IP/2016/NVA/WEF_FSA_FutureofGlobalFoodSystems.pdf
Xu, Z., Li, C., Zhang, C., Yu, Y., van der Werf, W. and Zhang, F. (2020). Intercropping maize and soybean increases efficiency of land and fertilizer nitrogen use; A meta-analysis. Field Crops Research, 246, 107661. doi:10.1016/j.fcr.2019.107661
Yamunarani, R., Govind, G., Ramegowda, V., Vokkaliga Thammegowda, H. and Ambarahalli Guligowda, S. (2016). Genetic diversity for grain Zn concentration in finger millet genotypes: Potential for improving human Zn nutrition. The Crop Journal, 4(3), 229-234. doi:10.1016/j.cj.2015.12.001
Yu, Y., Stomph, T.J., Makowski, D. and van der Werf, W. (2015). Temporal niche differentiation increases the land equivalent ratio of annual intercrops: A meta-analysis. Field Crops Research, 184, 133-144. doi:10.1016/j.fcr.2015.09.010
Zhang, C., Dong, Y., Tang, L., Zheng, Y., Makowski, D., Yu, Y., Zhang, F. and van der Werf, W. (2019). Intercropping cereals with faba bean reduces plant disease incidence regardless of fertilizer input; a meta-analysis. European Journal of Plant Pathology, 154(4), 931-942. doi:10.1007/s10658-019-01711-4

Appendix 1: List of abbreviations

BFA	Biodiversity for food and agriculture
CLAGD	Crop, livestock and aquatic genetic diversity
FBDG	Food-based dietary guidelines
FNER	Fertilizer equivalent ratio in relation to N
GMOs	Genetically-modified organisms
LER	Land equivalent ratio
NDCs	Non-communicable diseases
PAs	Pyrrolizidine alkaloids
SDG	Sustainable development goal

To explore the potential of nature to improve the quality of life

Wageningen Livestock Research
P.O. Box 338
6700 AH Wageningen
The Netherlands
T +31 (0)317 48 39 53
E info.livestockresearch@wur.nl
www.wur.nl/livestock-research

Wageningen Livestock Research creates science based solutions for a sustainable and profitable livestock sector. Together with our clients, we integrate scientific knowledge and practical experience to develop livestock concepts for future generations.

Wageningen Livestock Research is part of Wageningen University & Research. Together we work on the mission: 'To explore the potential of nature to improve the quality of life'. A staff of 6,500 and 10,000 students from over 100 countries are working worldwide in the domain of healthy food and living environment for governments and the business community-at-large. The strength of Wageningen University & Research lies in its ability to join the forces of specialised research institutes and the university. It also lies in the combined efforts of the various fields of natural and social sciences. This union of expertise leads to scientific breakthroughs that can quickly be put into practice and be incorporated into education. This is the Wageningen Approach.