Breeding4Diversity

A research agenda for increased genetic diversity in future circular and nature-inclusive production systems

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WAGENINGEN UNIVERSITY & RESEARCH

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S.J. Hiemstra[1,2], J. Buiteveld[3,2], G. Bonekamp[1], M.H. Thijssen[4], W.S. de Boef[4], B.G.H. De Groote[4], P.M. Bourke[5], J.A. Dieleman[5] and M.J.M. Smulders[5],

1 Wageningen Livestock Research
2 Centre for Genetic Resources, the Netherlands
3 Wageningen Environmental Research
4 Wageningen Centre for Development Innovation
5 Wageningen Plant Research

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Samenvatting
Meer biodiversiteit en genetische diversiteit in gewassen, bossen en landbouwhuisdieren wordt beschouwd als een belangrijke strategie voor veerkrachtige en duurzame land- en bosbouwsystemen die bijdragen aan klimaatmitigatie en -adaptatie. Veredeling en fokkerij moeten goed aangepaste rassen leveren die passen bij deze systemen. In dit rapport schetsen wij vijf visies van innovatieve land- en bosbouwsystemen en hebben deze gebruikt in focusgroepdiscussies met wetenschappers, fokkers en veredelaars, en pioniers. Met hen hebben we de bijdrage van biodiversiteit en genetische diversiteit aan de duurzaamheid en weerbaarheid van het systeem, de fok- en veredelingsdoelen, de toegang tot genetisch materiaal om die doelen te realiseren, en de prioriteiten voor onderzoek bediscussieerd. Hoewel systemen kunnen verschillen in het transitiepad, is strategisch onderzoek nodig, gericht op de relatie tussen een breder gebruik van genetische bronnen, verbetering van gunstige interacties tussen soorten/rassen, en de veerkracht van het gehele productiesysteem.
Summary
More biodiversity and genetic diversity in crops, trees, and livestock is considered an important strategy to improve resilience and sustainability of agricultural and forestry production systems that contribute to climate mitigation and adaptation. Plant and animal breeding need to provide well-adapted varieties and breeds that fit into these systems. In this report, we draw visions of five innovative agricultural production and forestry systems and used them in focus groups of scientists, breeders, and pioneer entrepreneurs to discuss the contribution of biodiversity and genetic diversity to the sustainability and resilience of the system, breeding goals, access to genetic material to realize the breeding goals, and the priorities for breeding and research. Although transition pathways can differ between systems, strategic research i should concentrate on the relationship between wider use of genetic resources, increasing beneficial species/breed/variety interactions, and the resilience of production systems.
Cover picture: René Smulders. Illustrations of production systems: Geert Gratama (www.geertgratama.nl).

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Foreword

Everyone is aware of the concerns about climate change. We know that too many pesticides and fertilizers are being used. In relation to the national, Dutch "nitrogen crisis", we realize the impact of excessive nitrogen deposition for nature and the environment. Biodiversity is declining fast. The loss of biodiversity will endanger the functioning of the planet. That is why we, in the Netherlands, are in the middle of a transition in agriculture, horticulture and livestock farming, and why forestry is also undergoing a transition. Biodiversity objectives must be an integral part of this transition because biodiversity contributes to sustainable and resilient production systems. The hypothesis is that biodiversity leads first to better and more efficient use of the available nutrients and raw materials. It also increases resistance to diseases and pests, and creates a buffer against the consequences of climate change. And – not to be forgotten – biodiversity provides a variety of well-adapted, robust species and varieties/breeds of crops, farm animals and trees. Making optimal use of biodiversity in future production systems can bring us great benefits.
In the past century, development of productive and adapted breeds/varieties has made a major contribution to the increase of the productivity and efficiency of our food and forestry systems. However, those systems are currently facing multiple challenges, including the need to lower input use, mitigation of, and adaptation to climate change. This also implies that new and improved breeds and varieties must be developed that are best suited for the production systems of this century and adapted to the changed climate. Luckily there is still a large genetic resources base that can be exploited for this purpose, and new knowledge and technologies will allow us to support the transition towards resilient and sustainable food and forestry systems in the future.
Wageningen University and Research (WUR) has always played a leading role in science and innovation for plant and animal breeding. In the context of the new and complex challenges, WUR, in collaboration with national and international partners and stakeholders, including the breeding sector, needs to continue investing in new knowledge, technologies and tools supporting the transition.
In this KB project we explored the system requirements that are relevant for future breeding investments, and we identified research priorities and research opportunities in the breeding domain. This report will provide the basis for the WUR research strategy on breeding and better use of crop, livestock and forest genetic resources for the next decades. Yet, the report is not only relevant for WUR researchers; policy makers can take measures to facilitate the use of a high diversity of starting material and stimulate the development and characterization of gene bank collections and breeding populations, in order to make best use of genetic diversity and to insure the present genetic diversity across and within species remains available.

Dr. Saskia Visser
Head of Programme Circular and Climate Neutral Society

Summary

The role of crop, livestock and tree breeding in the transition towards biodiverse production systems
In the past century, breeding has played an important role in developing improved and well-adapted breeds and varieties for agriculture and forestry systems. The past decades of focus on agricultural intensification have led to problems related to the use of pesticides, antibiotics, fossil fuels and fertilizers; environmental pollution and high greenhouse gas emissions; issues with animal welfare, human and animal health; and soil degradation. Moreover, intensive, highly productive monoculture farming resulted in the loss of biodiversity in and around agricultural production and forestry systems. Dutch and European policies now ask for a transition towards more sustainable, circular and resilient food and forestry systems. The challenges for this transition are further exacerbated by global warming.

Inclusion of higher levels of biodiversity and genetic diversity between and within species is considered an important strategy to develop new production systems which are resilient and sustainable and contribute to climate mitigation and adaptation. For such a new range of agricultural and forestry production systems, breeding needs to provide well-adapted breeds and varieties that fit into these systems.

Research questions
The study investigated: (i) which (combination of) species, varieties, breed and genetic diversity in crops, livestock and forest are needed or create added value in future production systems? and (ii) what opportunities and challenges arise for the crop, animal, and forestry breeding sectors. Based on the results, we formulated a research agenda for WUR and its partners and stakeholders in the breeding and seed sector.

Five innovative agricultural production and forestry systems
For our study we identified five innovative agricultural production and forestry systems: (i) mixed cropping; (ii) sustainable greenhouse horticulture; (iii) nature-inclusive dairy; (iv) climate-smart forestry; and (v) agro-forestry. In a mixed cropping system multiple crop species and varieties are grown together, with the aim of stimulating interactions between them, with insects and soil organisms, and potentially with non-crop diversity within the agricultural landscape. A sustainable greenhouse horticulture system is highly water-use efficient, with low use of chemical pesticides, and disease-resistant and robust varieties, adapted to more extreme climate conditions. The system makes use of sustainable electricity from sun or wind and implements new developments such as crop responses to particular light colours. The nature-inclusive dairy system is less intensive, grass-based, and makes make optimal use of the locally or regionally available feed resources, with more robust dairy cows. Climate-smart forests are species-rich, more resilient, with improved horizontal and vertical forest structure and variation in tree/shrub age. The agroforestry system has integrated trees into agricultural practices, and it may vary from two or three species (e.g., windbreaks or rows of trees in a grain field) to more than forty species or varieties (e.g., forest farming with many different vertical layers).

The role of breeding and the relevance of genetic diversity between and within species
In focus group discussion with scientists, breeders and pioneer entrepreneurs we investigated diversity- and breeding-related questions for each of the five systems and specifically addressed: (i) the contribution of biodiversity and genetic diversity to the sustainability of the system; (ii) breeding goals for a biodiverse system; (iii) access to genetic materials to realize the breeding goals; and (iv) priorities for breeding research. Key findings are indicated below.

Species diversity within systems
Multiple species in a system allow for complementarity in species traits and functions, and thus may include a multitude of functional relations between species, with positive effects on overall performance, resilience, resource-use efficiency, associated biodiversity and ecosystem services. Benefits are assumed to occur in all systems but are dependent on the species choice, the combination of species, and the local context, with relevance also determined by system boundaries and market opportunities. Different combinations of species in mixed crop, livestock, crop-livestock, forestry, or agro-forestry systems can play an important role in climate change adaptation and mitigation, e.g., by carbon sequestration or better resilience against drought or other extreme events.

Diversity within species
Optimal use of within-species genetic diversity is the basis for the breeding of new, improved, and well-adapted varieties and breeds. A change in production environments also requires a change of breeding goals. Climate change asks for crop varieties, animal breeds and forest provenances with increased adaptation to higher and more variable temperatures, heat, drought, and frost, as well as increased pest and disease resistance. Under more variable conditions adaptability becomes more important for crops, trees, and animals in all systems. Systems with different breeds/varieties or with genetic diversity within breeds/varieties of crops, livestock of tree species, may take advantage of complementarity, resulting in a spread of risks within the system. Because of long rotation times in forestry systems capturing enough adaptive genetic diversity within populations is crucial.

Diversity at landscape level
Production systems may be optimized at plot level, farming system level, forest level, regional/landscape level, or even at higher levels. Production systems are affected by the surrounding environment and vice versa. The landscape level is very difficult to address in breeding programmes, however, participatory approaches that include local selection may include the landscape component.

New and more complex breeding goals
Breeding of varieties or breeds optimized for highly diverse agricultural and forestry systems is complex. Complexity relates to issues like the need for appropriate assessment of genotype by environment interactions; alignment of breeding goals for different species within a system; measurement of functional relationships between species; consideration of new traits, also related to interaction among species; and the difficulty of assessing emerging characteristics such as resilience. For new minor crops or forest species, often only limited breeding and research has been done. Local adaptation becomes more important, considering a variety of local contexts and natural environments/landscapes. For forestry, models of the expected climatic conditions 50 to 100 years from now need to be considered, and livestock breeding goals will be influenced by changes towards more circular, integrated crop-livestock and nature-inclusive production system.

Improved technologies and new selection strategies
Breeding challenges may be partly solved by using improved technologies including automated phenotyping, genotyping, and artificial intelligence. However, breeding for increasingly complex production systems necessitates fundamental choices on selection context and the development of new selection strategies. Species (and breed/variety) interactions need to be assessed in the breeding program; however, it is impossible to do so for all advanced selections. Plant growth modeling approaches may provide a solution. Various approaches will need to be combined to develop the more integrated and diverse breeding programs of the future.

Screening of the existing genetic resource base for breeding
All new agricultural production and forestry systems will need new species diversity and adapted genotypes, however, the type of diversity that is required varies across systems, and may be in the form of new species, adapted breeds/varieties, or new traits. For crops and tree species, existing collections of genetic resources, both *ex situ* (genebank collections, provenance trials) and *in situ* (natural stands of indigenous trees and shrubs) need to be screened for relevant new traits, including traits important for species interaction, requiring that species are to be screened together. For livestock species, new breeding goals and traits also requires screening of the diversity of the full range of existing breeds (*in situ* and *ex situ*).

New minor crops and non-crop collections for breeding
More diverse systems offer opportunities for inclusion of new or minor crops, but for most of these species only limited genebank collections exist at best, and if they exist, they have not been characterized for the breeding challenges ahead. Starting new collections and expanding existing ones is an urgent challenge as natural ecosystems are declining, and species (and diversity within species) are being lost. Expanded collections should include the wild relatives of crop species of interest. Genebank collections are often non-existent for native species that provide ecosystem services, either incorporated in the system (crop, livestock, forestry, agroforestry) or next to it (field margins and hedgerows, surrounding natural elements), so their conservation and characterization needs to be initiated, *ex situ* and/or *in situ*.

Global access to genetic resources – the Nagoya Protocol and the International Treaty
For a selective group of food crops access to genetic resources for breeding is regulated through the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) by a multilateral system. For many other crops and species, the Convention on Biological Diversity (CBD) through its Nagoya Protocol regulates global Access and Benefit Sharing to genetic resources. International exchange of genetic resources for breeding and research is increasingly hampered since the adoption of the Nagoya Protocol. The current international legislation may exert constraints on developing more diverse production systems. If we want to expand genebank collections and to make better use of genetic diversity to support breeding for sustainable production system, the implementation of this type of legislation may need to be evaluated and improved.

Availability of reproductive material and seed systems
Availability of seed, reproductive material or genetic resources of crops, livestock and trees depends on the seed system, structure of the breeding sector and industry configurations, and the relationship between the farmers/end-users and providers of breeding material. The time dimension (duration from breeding to seed use, and frequency and efficiency of new genetics becoming available) and spatial dimension (scale in which they operate, varying from global to national or regional breeding and seed systems) are also relevant. Breeding and seed business models create both opportunities and boundaries to the way breeding can accommodate greater diversity in their programs. Strategies of breeding companies are determined by expected turnover and profit, combined with geographical, climate and specific market demands. Hence, the interest or ability of the established breeding sector to respond to demand for enhanced diversity may be limited, which means that additional public, public-private or private initiatives may be needed to foster access to more species and genetic diversity in future production systems.

Key research priorities
The following overarching strategic research questions need to be addressed in future research:

- Increased species and genetic diversity in breeding: which traits and interactions are relevant?
- New combinations of species: what kind of features and functionalities are important?
- What are the benefits of breed diversity or heterogeneous varieties within production systems?
- How to increase access to genetic resources for breeding, and how to enhance the availability of reproductive material for a range of systems?
- Adaptability and resilience: how to define and to implement in breeding programs?
- How to apply new breeding methods, new technologies and different breeding approaches?

In conclusion
Multiple challenges and transitions that are needed in agriculture and forestry require an integrated approach. Context-specific optimization of production systems will result in a larger diversity of resilient and sustainable future food production and forestry systems, and increased diversity within production systems. Crop, tree and livestock species diversity, and the genetic diversity within species, is the basis for the functioning, the resilience and productivity of production systems. Increasing genetic diversity within systems also implies more interactions and increasing complexity.

Further strategic research in the context of crop, tree and livestock breeding should particularly investigate the relationship between wider use of genetic resources, increasing beneficial species/breed/variety interactions, and the resilience of production systems. The increased (data) complexity must be managed in research and breeding, making best use of new technologies, methods, and breeding approaches. These are the domain of WUR research. Implementation of the findings poses challenges for breeding companies, public breeding institutes and participatory networks, seed and plant material suppliers, as well as farmers.

1 Introduction

1.1 Challenges and drivers for new production systems

In the context of increasing food security, over the past decades agricultural production systems mainly focussed on increasing efficiency and productivity and optimizing profits. This resulted in highly productive systems with multiple challenges, including excessive use of pesticides, antibiotics, fossil fuels and fertilizers; environmental pollution and high greenhouse gas emissions; issues with animal welfare, human and animal health; and soil degradation. Moreover, the focus on highly productive monoculture farming resulted in the loss of biodiversity in agricultural production and forestry systems, which is continuing at an ever-faster rate. Currently we produce more food with fewer crop and livestock species, and with a much narrower genetic diversity within these species. Due to the increased scale of agriculture, also natural elements in and around production areas got lost. Global warming and increasing water scarcity put additional challenges on our current agricultural production and forestry systems.

To increase sustainability of production systems, social, economic, and environmental concerns need to be addressed. Dutch and European policies are now supporting a transition towards more sustainable, circular, and resilient food and forestry systems. Examples are the vison of the Dutch government on circular agriculture, the Dutch Forest Strategy and, at the level of the European Union, the European Green Deal. An excellent opportunity to assure that the "starting materials" for those productions systems meet the expectations of those systems.

1.2 Diversity between and within production systems

As indicated above, nowadays only a limited number of species, varieties and breeds are dominant in agriculture worldwide. Regarding crop production, out of the 6,100 crop species cultivated for food, only 200 have a significant production level at a global scale. Moreover, 66% of the total crop production worldwide comes from only nine crop species[1]. For livestock production a similar trend is observed, as local breeds have gradually been replaced by higher yielding breeds. For forestry, currently 30% of Europe's forests have only one tree species, 51% have only two to three tree species, and only 5% of the forests have six or more tree species.[2] Besides the reduction of livestock and crop genetic diversity at farm level or at production system level, due to years of specialisation and upscaling of agriculture, intensification of agriculture also led to a reduction of (non-productive) landscape elements in and around the agricultural fields. At the same time, it is acknowledged that higher levels of biodiversity and genetic diversity in production systems can not only improve the system's resilience and sustainability, contribute to climate mitigation and adaptation, and support local biodiversity, but also have the potential to increase crop production.[3]

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

[2] EEA, 2020. State of nature in the EU. Results from reporting under the nature directives 2013-2018. European Environment Agency.

[3] Beillouin, D., Ben-Ari, T., Malezieux, E., Seufert, V. and Makowski, D., 2021. Positive but variable effects of crop diversification on biodiversity and ecosystem services. Global Change Biology 27: 4697-4710. https://doi.org/10.1111/gcb.15747

1.3 Breeding sector and research questions

The Netherlands has strong animal and crop breeding sectors, which have shown a cumulative and positive impact of crop and animal breeding on efficiency and sustainability of production systems over the past decades. These knowledge intensive sectors have been successful in catering for the continuously changing demands of their customers. The sectors have a key contribution to make in supporting the development of more diverse agricultural production and forestry systems, making the reproductive materials available, in terms of right crop, animal and tree species, varieties and breeds, with the right traits. This calls, for example, for a better characterization of genetic diversity between and within species, knowledge about relevant traits, and the development and application of new methods and approaches to support breeding programmes.

In relation to challenges and opportunities for breeding and research we investigated the following key questions:

1. Which (combination of) species, varieties, breed and genetic diversity in crops, livestock and forest are needed or create added value in future production systems?
2. What opportunities and challenges arise for the crop, animal and forestry breeding sectors?
3. What should the research agenda of Wageningen University & Research (WUR) focus on?

1.4 Study approach

We described five different examples of innovative agriculture and forestry production systems. We developed drawings that graphically represent a vision with idealised aspects of the five production systems. For each of these five systems we organised a focus group discussion, which involved scientists, breeders and pioneer entrepreneurs in the field. We addressed the following questions:

1. What is the role of biodiversity in species, varieties and breeds for the future and sustainability of the production system?
2. What are the technical breeding goals and requirements to reach this biodiverse and sustainable future production system?
3. Is the genetic material available to reach these goals? Why not? (technical/breeding or market/practical limitations?)
4. What opportunities and challenges does this bring for crop, tree, and animal breeding? I.e., what should the (WUR) research agenda focus on?

This report provides a summarized description of the five systems (chapter 2), presents the outcomes of the focus group discussions (chapter 3), and synthesizes the main findings (chapter 4). It concludes with the elements of a strategic research and innovation agenda to contribute to the transition towards a range of resilient and sustainable future agricultural production and forestry systems (chapter 5).

2 Five innovative production systems

The five innovative agricultural production and forestry systems that are relevant for the Dutch agriculture and forestry context are characterized by high crop, livestock and/or tree diversity within the individual systems. The systems cover various combinations of crop, animal and tree species, different management practices (e.g., more or less intensive), and different horizons for implementation.

The production systems are:

1. Mixed cropping
2. Sustainable greenhouse horticulture
3. Nature-inclusive dairy
4. Climate smart forestry
5. Agroforestry

Below we present a short description of these production systems, starting with the challenges driving the development of these systems, and providing a first indication of implications for the breeding sector.

2.1 Mixed cropping

The challenge

Agricultural production is currently concentrated in an increasingly small number of key or staple crop species. With the increased scale of operation of cropping systems over the last half century, the diversity per area and per unit of time in these systems has also decreased, sometimes resulting in a single crop variety grown in a large area of farmland. With the practice of crop rotation, monoculture is spatial rather than temporal, but this is suboptimal when only few different crops are part of the rotation. Often non-productive landscape elements such as field margins, hedges, rows of trees and forest patches have been removed, thereby decreasing ecosystem and species diversity in and around the field.

Climate change, loss of biodiversity, concerns about excessive use of pesticides, fossil fuels and fertilizers, and the burden on nature and the environment, make a transition in agriculture necessary[4]. There is a renewed interest in nature-inclusive and more resilient farming systems, which manage and maintain biodiversity and valuable landscapes[5]. The challenge is to design these systems in such a way that along with a diversity of ecosystem services, they show resilient production with maintained or even increased crop yields.

[4] Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., et al., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347:1259855. doi: 10.1126/science.1259855

[5] Brooker, R.W., George, T.S., Homulle, Z., Karley, A.J., Newton, A.C., Pakeman, R.J., et al., 2021. Facilitation and biodiversity–ecosystem function relationships in crop production systems and their role in sustainable farming. J. Ecol. 109, 2054–2067. https://doi.org/10.1111/1365-2745.13592

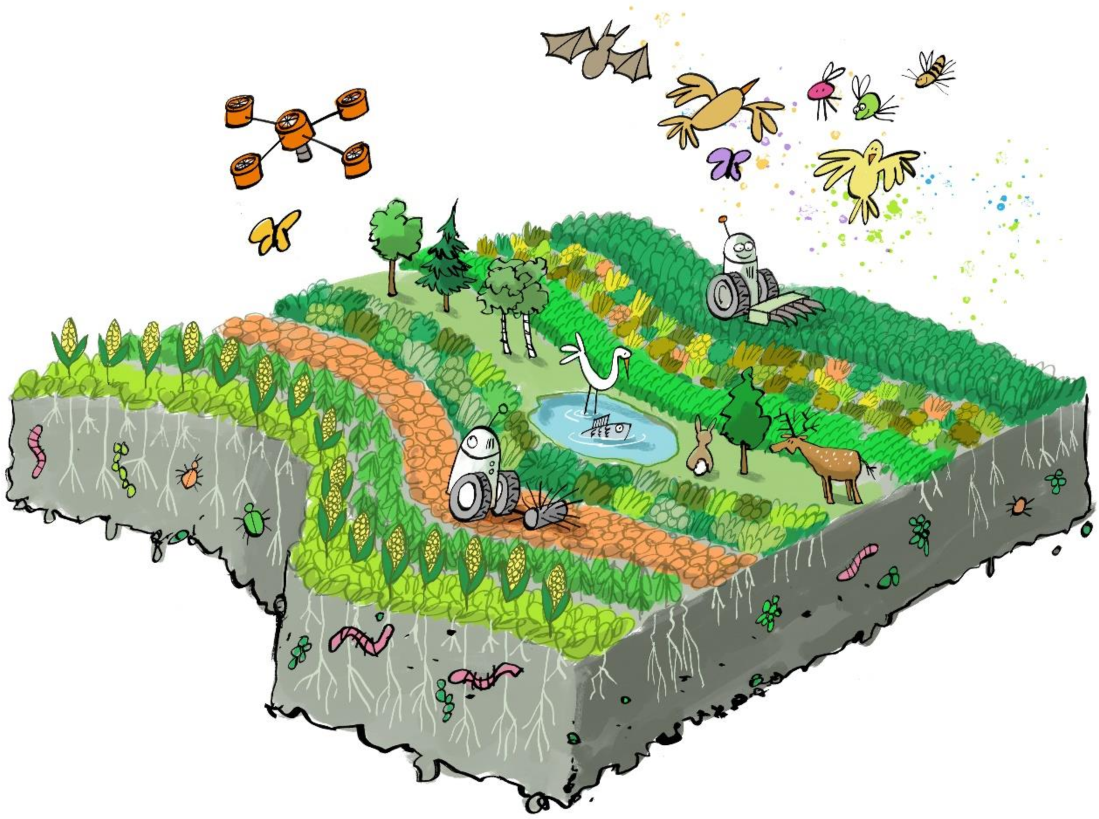

Figure 1 *Vision of a mixed cropping system.*

The mixed cropping system

Mixed cropping with intercropping/strip cultivation is one of the most promising practices in this regard[6]. It is characterized by increased species diversity on the agricultural fields, while increased genetic diversity within one or more of the crops (multiple varieties of a single crop, genetically mixed varieties) may be added into the mix[7]. Practically, this means that multiple varieties and crop species are grown together. The aim is to stimulate interactions between them, and interactions with insects and soil organisms. Strip cultivation is one implementation, in which the crop species and varieties are grown alongside each other[8]. Pixel farming makes these patches even smaller. Furthermore, the system can be combined with increased non-crop diversity within the agricultural landscape of wild species in field margins, hedges, shrubs, trees and, where appropriate, ponds.

The potential advantages of mixed cropping systems include more resilient production[9], production of quality food with increased diversity of products, and lower pressure on nature and the landscape[10]. Potential disadvantages include a lower efficiency per kg of product with higher production costs, and lower farmer income from primary products. The latter may to be compensated by additional income from ecosystem services. To achieve its potential, mixed cropping still needs to address a multitude of challenges, including the necessity for more complex agricultural designs in space and time, tailored machinery, optimal combinations of crops, and adapted crop varieties.

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[6] Martin-Guay, M.O., Paquette, A., Dupras, J. and Rivest, D., 2018. The new green revolution: sustainable intensification of agriculture by intercropping. Sci. Total Environ. 615, 767–772.

[7] Wuest, S.E., Peter, R. and Niklaus, P. A., 2021. Ecological and evolutionary approaches to improving crop variety mixtures. Nat. Ecol. Evol. 5, 1068–1077. doi: 10.1038/s41559-021-01497-x

[8] Van Oort, P., Gou, F., Stomph, T. and Van Der Werf, W., 2020. Effects of strip width on yields in relay-strip intercropping: a simulation study. Eur. J. Agron. 112:125936. doi: 10.1016/j.eja.2019.125936

[9] Raseduzzaman, M., and Jensen, E. S. 2017. Does intercropping enhance yield stability in arable crop production? A meta-analysis. Eur. J. Agron. 91, 25–33. doi: 10.1016/j.eja.2017.09.009

[10] Brooker, R.W., Bennett, A.E., Cong, W.F., Daniell, T.J., George, T.S., Hallett, P. D., et al., 2015. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phytol. 206, 107–117. doi: 10.1111/nph.13132

Breeding strategies

Current breeding strategies focusing on the selection of the best performing genotypes in pure stands and have both overlooked the benefits of positive interspecific interactions between crops or genotypes in a mixed crop design, and the importance of root and shoot trait plasticity for performance. Re-designing breeding programmes to accommodate intra-specific interactions and compatibilities (with potentially multiple different intercropping partners) requires a shift in goals and in approaches[11]. The new breeding goals will increase the complexity of these programmes.

2.2 Sustainable greenhouse horticulture

The challenge

Greenhouse horticulture is the cultivation of crops in protected environments, ranging from low tech systems such as tunnels covered with plastic, mid-tech systems including heating, to high-tech glasshouses, with heating, ventilation via windows, dehumidification ducts, CO_2 supply and assimilation lighting, where indoor conditions are hardly dependent on outside climate anymore[12]. Current greenhouse production systems provide year-round healthy, fresh food crops and ornamentals. However, these cultivation systems come at the cost of high energy consumption[13]. On the other hand, water use efficiency may be up to 60x higher than in open field cultivation[14], and the sector can reuse CO_2 exhaust gases from industry. Over the last decades, greenhouse companies have increased in size, so that frequently multiple hectares of one variety of one crop is cultivated. Over the season, climate conditions are maintained as uniform as possible, to generate a stable, constant level of high-quality production. Although greenhouses are ”closed” systems, they are sensitive to outside conditions. Climate change has increased temperatures in summer, giving rise to higher temperatures within greenhouses. On the other hand, the current energy crisis makes heating greenhouses in winter less economically viable, which may result in lower greenhouse air temperatures in winter.

To maintain the "license to produce", protected cultivation must develop into all-electric systems, with input of sustainable electricity from sun or wind. Furthermore, the system must adapt to more extreme climate conditions, due to climate change, and to legislation on CO_2 emission[15].

The sustainable greenhouse horticulture system

These changes in the system require a re-design of the varieties that fit these systems best: they must be robust (capable to deal with high-low temperatures), with an open crop architecture, efficiency of CO_2 use, disease resistances, uniformity, and high productivity. Furthermore, current experiences on crop responses to different light spectra show that there is still a considerable amount of unexplored genetic variation to climate conditions, at the benefit of protected cultivation and breeding industry.

At the same time, further intensification of production systems is ongoing towards closed, day-light-less conditions ("vertical farms"), which expands greenhouse horticulture into urban areas. Such closed and completely controlled systems will require new varieties that have different responses to climate conditions, such as altered air movement affecting transpiration and LED light spectrum that affects plant morphology. This will stretch crop responses beyond the boundaries of what we assumed was possible.

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[12] Stanghellini, C., Van 't Ooster, B. and Heuvelink, E., 2019. Greenhouse horticulture. Technology for optimal crop production. Wageningen Academic Publishers, 300 pp. ISBN: 978-90-8686-329-7.

[13] De Gelder, A., Dieleman, J.A., Bot, G.P.A. and Marcelis, L.F.M., 2012. An overview of climate and crop yield in closed greenhouses. Journal of Horticultural Science and Biotechnology 87 (3), 193-202.

[14] Nederhoff, E. M., & Stanghellini, C., 2010. Water use efficiency of tomatoes – in greenhouses and hydroponics. Practical Hydroponics & Greenhouses, 2010(115), 52-59.

[15] Hemming, S., Balendonck, J., Dieleman, J. A., De Gelder, A., Kempkes, F. L. K., Swinkels, G. L. A. M., ... and De Zwart, H. F., 2017. Innovations in greenhouse systems-Energy conservation by system design, sensors and decision support systems. Acta Hortic, 1170, 1-15.

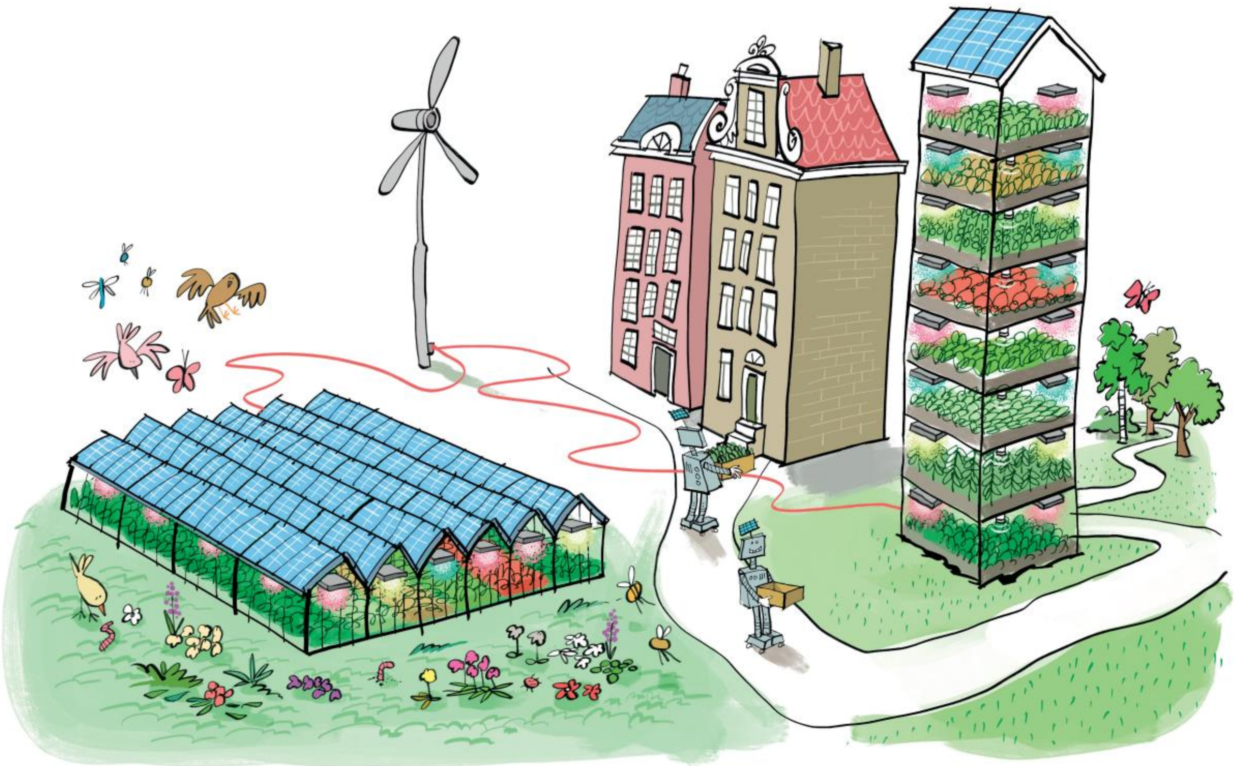

Figure 2 *Vision of a sustainable greenhouse horticulture system.*

Breeding strategies

Current breeding strategies focus on the selection of the best performing genotypes, with sufficient resistances against diseases, in new types, colours or shapes. However, greenhouse horticulture faces several changes, including climate change with more extreme heat waves, worldwide climate goals which will set maximum limits to CO_2 emission, and thereby the use of fossil energy, and the demand of an increasing population for year-round availability of healthy and fresh products. Other developments that affect the system are the continuous reduction in number of available crop protection products, which demands breeding for resistance, increased options for automation in the greenhouse, which require crop characteristics that are accessible for cameras and robots, increased company size, shortage of (skilled) labour, etc. These changes have consequences for the demands for new varieties. New technological developments, such as the use of different light colours via LED lighting, have unlocked a new set of crop responses yet unknown. Together with the breeding industry, the new production systems should be described, and new ideotypes that optimally exploit these conditions should be established. The potential contribution of functional interactions between multiple crop species in the system should be taken along in the ideotype definitions.

2.3 Nature-inclusive dairy

The challenge

The balance between livestock production and the natural environment is currently disrupted. Some major causes are the high use of imported feed, artificial fertilizers, pesticides and preventive antibiotics, and the high animal densities and nutrient and greenhouse gas emissions in the livestock sector[16]. Therefore, a transition is needed in the livestock sector, to develop more sustainable and resilient future livestock systems. Those future livestock systems will need to fully integrate the major societal and environmental concerns, including climate change mitigation and adaptation, biodiversity loss, environmental burdens, and animal welfare, to stay societally relevant and acceptable. At the same time, the farmer should be able to obtain a living out of it.

In the Netherlands more than 50% of the agricultural land is grassland, of which a substantial proportion can only be used for grazing or livestock production. At a global level, depending on the exact definition of grasslands, about one-third of the global land area are grasslands. In less favoured grassland areas, livestock systems are often the only possible production systems, and these systems also provide a range of ecosystem services[17].

Figure 3 *Vision of a nature-inclusive dairy system.*

The nature-inclusive dairy system

Grasslands, in particular permanent grasslands, can have a high nature value[17], prevent erosion and play an important role in carbon sequestration.

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[16] Steinfeld, H., Food and Agriculture Organization of the United Nations, and Livestock, Environment and Development (Firm), 2006. *Livestock's long shadow: environmental issues and options*. Food and Agriculture Organization of the United Nations.

[17] Bengtsson, J., Bullock, J. M., Egoh, B., Everson, C., Everson, T., O'Connor, T., ... & Lindborg, R. (2019). Grasslands—more important for ecosystem services than you might think. Ecosphere, 10(2).

Feeding livestock from less favoured grassland areas or with by-products reduces the feed-food competition. Less import of high-quality feed resources and less use of fertilizer will lead to more extensive farming systems, and also more variable farming conditions and feed quality can be expected. An important goal of such extensive farming system is to make optimal use of the locally/regionally available feed resources. More robust and less productive dairy cows could fit very well in this resource-efficient, grass-based food system[18]. This is different compared with the current, more intensive dairy systems.

In addition to the main aim of producing food products, nature-inclusive dairy cattle systems contribute to a range of ecosystem services. The relevant types of ecosystem services depend on the local context. These systems can make a major contribution to both climate change mitigation and adaptation. Carbon sequestration in (permanent) grasslands is potentially a major climate mitigation strategy, and nature-inclusive, grassland systems can also play an important role in climate change adaptation (e.g., flood prevention). This, however, is not the case for the grasslands on Dutch peat soils. Prevention of greenhouse gas emissions from peat soils is mostly done by raising the water table, which leads to more swampy circumstances in the fields. The question raises what type of (dairy) cattle would be most suitable for these different areas.

Increasing concerns about animal health, welfare and longevity, in relation to criticism on industrial livestock production, may lead to more interest among consumers to buy livestock products from grazing systems of known origin through short supply chains. In addition, the milk composition, and the fatty acids in particular, of cows that are mostly grazing and fed with (fresh) grass products is more in line with human dietary requirements than milk from more industrial systems[19,20].

Breeding strategies
Cattle breeding goals and the emphasis on particular traits will be different for nature-inclusive dairy systems compared with more intensive dairy systems. Different traits e.g. robustness related, may become relevant, and prioritization of traits (the economic value) will depend on the local context and the vision of farmers. Hence breeding programmes should focus on different requirements of a range of production systems. Either breeding programmes can be focussed on one production system, or breeding programs can define a portfolio of breeding goals, catering a variety of production systems. Tailor-made breeding program design is needed. Moreover, extensive, nature-inclusive grassland systems will also require different varieties of grass or different types of grass mixtures, which may also have impact on breeding programmes.

2.4 Climate-smart forestry

The challenge
Due to climate change forests are more vulnerable to disturbances including fires, insect outbreaks, invasive species, and storms, which all reduce forest productivity and cause severe economic losses. This is particularly true for forests with mono species and even-aged stands. Air pollution may exacerbate the impacts of climate change resulting in enhanced soil acidification. It is expected that forests will not be able to adapt adequately to these changing circumstances.[21] [22] [23]

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[18] Van Hal, O., De Boer, I J M., Muller, A., De Vries, S., Erb, K.H., Schader, C., ... and Van Zanten, H. H. E., 2019. Upcycling food leftovers and grass resources through livestock: Impact of livestock system and productivity. *Journal of Cleaner Production*, *219*, 485-496.

[19] Slots, T., Butler, G., Leifert, C., Kristensen, T., Skibsted, L.H., and Nielsen, J.H. 2009. Potentials to differentiate milk composition by different feeding strategies. *Journal of dairy science*, *92*(5), 2057-2066.

[20] Średnicka-Tober, D., Barański, M., Seal, C.J., Sanderson, R., Benbrook, C., Steinshamn, H., ... and Leifert, C., 2016. Higher PUFA and n-3 PUFA, conjugated linoleic acid, α-tocopherol and iron, but lower iodine and selenium concentrations in organic milk: a systematic literature review and meta-and redundancy analyses. *British Journal of Nutrition*, *115*(6), 1043-1060.

[21] Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M.J. and Marchetti, M., 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and Management, 259 (4), 698-709

[22] Lindner M., Fitzgerald, J.B., Zimmermann, N.E., Reyer, C., Delzon S., van der Maaten E., Schelhaas M.J., Lasch P., Eggers J., van der Maaten-Theunissen M., Suckow F., Psomas A., Pouler B., Hanewinkel M., 2014. Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? Journal of Environmental Management 146:69-83. doi:10.1016/j.jenvman.2014.07.030

[23] UNECE/FAO 2021 Forest Sector Outlook Study 2020-2040 Geneva Timber and Forest Study Paper 51 ECE/TIM/SP/51. United Nations, Geneva. https://unece.org/sites/default/files/2021-11/SP-51-2021-11_0.pdf

Therefore, the resilience of forest systems needs to increase, i.e., the ability of a forest to absorb disturbances and re-organize under change to maintain similar functioning and structure[24].

At the same time the demand for forest products and services continues to increase. Forests provide important ecosystem services such as water purification, biodiversity conservation, recreation, and flood regulation. Healthy forests are needed to sustain the provision of these diverse ecosystem services.

Forests should contribute to climate change mitigation by sequestration and storage of carbon in forests and soils. For reduction of the consumption of fossil-based materials, growth of forests could be increased and more products from wood should be produced. Cascading use of wood is an important aspect of the forest's and forest sector's contribution to the circular bioeconomy.

Figure 4 *Vision of a climate-smart forestry system.*

The climate-smart forestry system

The Sustainable Development Goals (SDG's), the Paris Climate Agreement, and EU policies including the EU forest strategy for 2030[25], set new demands for European forests. Sustainable forest management is the leading concept for managing and using forests[26]. However, climate targets will require a new role for forests and the forest sector in contributing to climate mitigation. Therefore, a change is needed to make forest systems more resilient and to make optimal use of their climate mitigation potential. Climate-smart forestry is one approach for achieving these goals[27,28].

[24] Scheffer, M., 2009. Critical Transitions in Nature and Society. Princeton University Press, Princeton, NJ.

[25] Find the New EU Forest Strategy for 2030 at the EUR-Lex website: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0572

[26] See website of Forest Europe: https://foresteurope.org/workstreams/sustainable-forest-management/

[27] Kauppi, P., Hanewinkel, M., Lundmark, T., Nabuurs, G.J., Peltola, H., Trasobares, A. and Hetemäki, L., 2018. Climate Smart Forestry in Europe. European Forest Institute.

[28] Nabuurs, G.J., Delacote, P., Ellison, D., Hanewinkel, M., Lindner, M., Nesbit, M., Ollikainen, M. and Savaresi, A., 2015. A new role for forests and the forest sector in the EU post-2020 climate targets. From Science to Policy 2. European Forest Institute.

The aim of climate-smart forestry is that adaptation and mitigation of climate change is mainstreamed in forest management practices, while at the same time provisioning of other important ecosystem services and forest functions such as wood production, biodiversity, water purification and recreation is maintained.

In the Netherlands climate-smart forestry may be introduced through the conversion of low-productive conifer forests[29] into species-rich and more resilient forests with improved horizontal and vertical forest structure, e.g., including shrub layers and different age classes using small-scale management interventions. Sequestration of CO_2 is increased by optimizing the increment and standing stock in the forest. This may include frequent thinning and planting of species and provenances with faster growth. To aim for quality wood in order to extend the storage of carbon in wood products, provenances with good wood quality properties are planted. Other characteristics of such a climate-smart forest could include soils with sufficient buffering capacity and availability of nutrients and the introduction of mycorrhiza, as these have beneficial effect on nutrient uptake and hence growth and vitality of a range of tree species.

Potential advantages of such high-diversity forests could be higher productivity compared to monocultures, a more stabilized productivity over time, high carbon sequestration over longer periods of time, and accelerated adaptation to climate change. There may be disadvantages in terms of increased costs of management and harvesting, more flexibility of the wood processing industry will be required, and new markets and products need to be sought. Also balancing between adaptation and mitigation might be challenging. For instance, replacing one species for another might have economic consequences for the timber production.

Breeding strategies
In future climate-smart forests the adaptability and resilience will be enhanced through increased diversity and heterogeneity at different levels (genetic diversity within species, species diversity and diversity at the landscape level) and using species and planting material that are better adapted to climate change and less vulnerable to diseases and pests. Traits such as disease resistance and tolerance to abiotic stress will become more important. Since forest ecosystems and climates are very diverse across Europe, climate-smart forestry measures may be regionally very different. This requires choosing appropriate plant material in terms of species or mix of species, provenances, and varieties suited for the local conditions. At the same time enhanced CO_2 sequestration will ask for fast-growing material. To increase the amount and duration of storage of carbon in wood products, varieties and seed sources with good wood quality properties are needed. This will bring new challenges and goals for selection and testing and new tree improvement programs.

2.5 Agroforestry

The challenge
Agroforestry is a well-known practice, which is widespread, particularly also in developing countries. Agroforestry systems are regaining interest nowadays because they can contribute to our current environmental and societal challenges. Agriculture, forestry, and other land uses are responsible for 21% of the world's total greenhouse gas emissions.[30] Unsustainable agriculture practices, including the use of pesticides, result in loss of biodiversity, soil degradation and loss of soil fertility. The main advantages of agroforestry are the diversification of products (including special wood types, different crops, and livestock products), protection of crops and animals by the trees, and a positive impact on water management, soil health, and general biodiversity. Agroforestry can also play an important role in reducing climate impact due to its carbon sequestration potential and climate adaptation[31]. Modern agroforestry faces new challenges and questions, such as how to incorporate agroforestry in modern large-scale agricultural systems while maintaining productivity and efficiency of the system management.

[29] These young forests on poor sandy soils usually consist of former monocultures of conifers and oak and are the most common forest type. Nowadays, an estimated 40,000 hectares of these low-yielding forests exist, with low additional growth and CO2 sequestration (Kremers and Boosten, 2019)

[30] FAO. 2016. State of food and agriculture – climate change, agriculture and food security. http://www.fao.org/3/i6030e/i6030e.pdf

[31] In the ambition of the EU to become climate neutral a roadmap for planting a 3 billion additional trees by 2030 is prepared. https://ec.europa.eu/info/sites/default/files/communication-annex-eu-biodiversity-strategy-2030_en.pdf

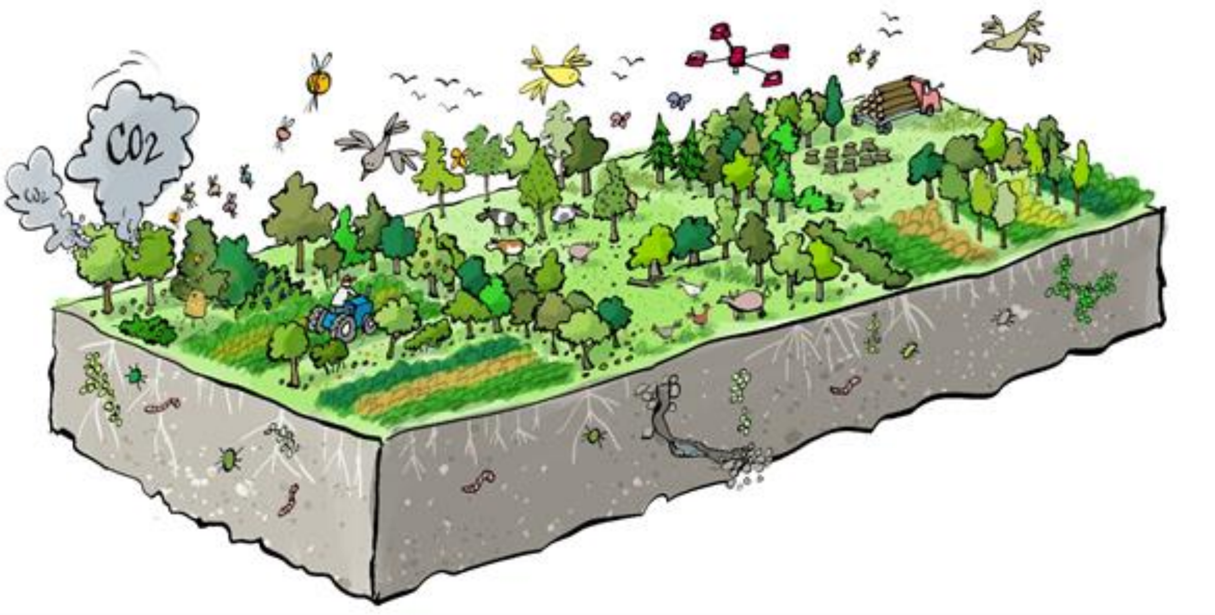

Figure 5 *Vision of an agroforestry system.*

The agroforestry system
There are three main systems of agroforestry: (i) Agrisilvicultural: crops + trees; (ii) Silvopastoral: grassland/animals + trees; and (iii) Agrosilvopastoral: crops + grassland/animals + trees. These systems have in common that trees are integrated in agricultural practices. These agroforestry systems can exist in numerous forms. They may be based on only two or three species, for instance windbreaks or rows of trees in a grain field (so-called alley-cropping), but they can also contain more than forty species or varieties, for instance forest farming with many different vertical layers[32].

A modern agroforestry system may help to solve important ecological, climate and biodiversity challenges in traditional high-input agricultural systems, while at the same time enabling the production of food, wood products and fodder for livestock. The system can be designed in such a way that it is adapted to modern farm machinery and productivity is optimized. Suitable and adapted tree species and varieties are combined with agricultural crops and/or livestock species to provide the farmer with extra income from, e.g., high-quality timber, bioenergy, or non-wood products (nuts, fruits) without necessarily reducing the production of agricultural crops or animal products. This demands specific characteristics of the trees and the design, but also includes applying new innovative techniques (e.g., drones) and adapting machinery (e.g., lightweight tractors) to these new systems.

Breeding strategies
Specific questions related to the design of agroforestry systems include identification of the most appropriate spatial and temporal arrangements of the woody and non-woody components, and, depending on the functions and products of the system, how to choose appropriate species and optimal combinations of species (crops, livestock, and trees).

[32] Groot, E. D., & Veen, E. 2017. Food forests: an upcoming phenomenon in the Netherlands. Urban Agriculture Magazine, (33), 34-36.

3 Stakeholders' perspectives on the selected production systems

Five focus group discussions were organised - one for each production system - to obtain input from breeders, pioneer entrepreneurs, experts, and other stakeholders on the combinations of species, breeds and genetic diversity needed to make the selected production systems sustainable, innovative, circular and resilient, and on the role of breeding and seed systems to realise these production systems. We discussed opportunities and challenges for each production system in groups varying from six to ten stakeholders from the public and private sector.

Four main questions were discussed in each group:

1. What is the role of biodiversity in species, varieties and breeds for the future and sustainability of the production system?
2. What are the technical breeding goals and requirements to reach this biodiverse and sustainable future production system?
3. Is the genetic material available to reach these goals? Why not? (technical/breeding or market/practical limitations?)
4. What opportunities and challenges does this bring for crop, tree, and animal breeding? I.e., what should the (WUR) research agenda focus on?

A summary of the focus group discussions is given in the sections below.

3.1 Mixed cropping

Relevance and future of the system
The participants of the focus group discussion on the mixed cropping system perceived the illustration of the production system (see Figure 1) as highly relevant. The diversity, the soil quality, the incorporation of modern technology and the holistic approach were seen as positive elements of the system. On the other hand, doubts were shared about the practical and financial feasibility of this system, as it will require a higher level of maintenance work and also a transition of agricultural equipment.

Role of diversity in the system
The role and importance of diversity in the system was acknowledged by the participants, first of all in its contribution to overall biodiversity and by creating habitats for many species. Diversity in space and time was suggested to increase the resilience of the system itself: a more stable yield, less disease pressure and fewer inputs needed. Diversity in soil and soil life was mentioned to form the basis for that, although more research is needed to study the causal relations. More knowledge is also needed on the interaction between different species and genotypes when they are grown next to each other.

Breeding goals and requirements
Breeding crops for mixed systems will need to consider additional aspects when compared to breeding for monocultures. Crop species should not compete too much with each other for resources, although they still must compete with weeds. That requires a good balance between competition and cooperation between plants throughout the whole growing season. Breeding for mixed cropping needs to consider the complementarity of species or varieties, in above- and below-ground architecture, in the moment of harvesting, and in terms of the soil life that the plants "create" around them.

These interaction traits have not been well-studied and heritabilities (how much of it is related to the genetics of the crop) of such traits are hard to estimate in complex systems[33]. Studying them will require new methodologies and adjusting current methodologies. For instance, phenotyping of individuals will also have to be done on border rows instead of only at the middle of a plot. Still, selection for individual plant health and resistance to (abiotic) stress will stay important too, since spraying pesticides is not a first choice in intercropping systems.

Access to genetic resources
Accessibility of plant genetic resources for relevant traits could be improved by setting up collections for species for which they do not yet exist. Screening of already existing gene bank material could also help to find suitable genetic material. Large-scale data collection, also of the more complex traits, is required to be able to find accessions with the right traits. Some traits may not be assessed in the current variety testing. In terms of use, heterogenous varieties could be a way to increase the level of biodiversity in the fields. Even new crop species with special intercropping features could be developed.

Key research topics
Several topics were identified that need further study. These include issues like practical field designs of mixed cropping systems and the use of machinery in it. Also studying the role of bacteria and fungi in relation to soil health and the mixed cropping system is important. Next to these technical issues, the feasibility of the business model, including additional options for product marketing needs to be investigated. The main topics that came up in the discussion around plant breeding for mixed cropping systems that need further study are:

- The synergy with other transitions, such as the protein transition, and mitigation of climate change in terms of combined long-term breeding goals
- The identification of the right combinations of species and varieties and the development of new varieties for these combinations
- The potential of new crops in mixed cropping systems, including 'forgotten' vegetables and perennial species
- Information on new and complex traits relevant for intercropping systems and heritability of those traits
- Use of advanced technologies for data collection, like drones and artificial intelligence, on the performance of crops in different combinations, and new, suitable equipment and machinery, including robotics for a diversity of systems.

3.2 Sustainable greenhouse horticulture

Relevance and future of the system
Focus group participants rated the illustration of the sustainable greenhouse horticulture system (Figure 2) as quite relevant. They appreciated seeing visions of different production systems next to each other, and they noticed the vision for greenhouse horticulture as an intensive, efficient, high-value system which generates high-quality products. The illustration provoked an interesting discussion on the most suited location for horticulture (should it be within a residential area?), the size and scale of the system (must it be higher than the residential buildings?) and how to connect the sustainable greenhouse horticulture system to society (inside-outside connection).

Role of diversity in the system
In terms of the role of diversity in the greenhouse horticulture system we must differentiate between 'open' and 'closed' systems. The advantage of an open greenhouse system is that it can make use of natural enemies which are part of the biodiversity outside the system for pest management; the advantage of a closed greenhouse system is that especially young plants can be protected well from diseases for which such natural enemies are not available.

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[33] Bourke, P.M., Evers, J.B., Bijma, P., Van Apeldoorn, D., Smulders, M.J.M., Kuyper, T. Mommer, L. and Bonnema, G., 2021. Breeding beyond monoculture: putting the 'intercrop' into crops. Frontiers in Plant Science 12: 734167. https://doi.org/10.3389/fpls.2021.734167

Increasing the diversity within the system (mixing of crops) to enhance the ability to deal with changing circumstances requires systems that can be adapted, which is easier with smaller compartments. This needs further investment in technology.

Breeding goals and requirements
Breeding for resistance against pests and diseases, including new pests and diseases moving into our area, partly due to the changing climate, has high priority. New varieties need to be adapted to future horticultural systems; seed companies may advise on how to optimize cultivation practices. Also, automation in greenhouse horticulture puts specific requirements to the variety (e.g., in relation to harvesting characteristics). Breeding for cultivation in monocultures differs from breeding for mixed cropping. Pest and disease management in systems with mixed crops will lead to less homogeneous products and may go at the expense of lower production levels; a prerequisite is that consumers accept these ‘less perfect’ products.

Access to genetic resources
Access to genetic resources, including wild relatives, is extremely important to breed for resistance. Genetically heterogeneous varieties (multilines) may be considered as another approach for disease management. To fight pest and diseases in the greenhouse, traits to support biological control may be considered as breeding goals as well, for instance pollen quality in sweet pepper and extrafloral nectaries in rose.

Key research topics
Participants of the focus group discussion identified various research topics for optimizing systems for sustainable greenhouse horticulture. How to develop those complex systems with multiple crops, including CAM (crassulacean acid metabolism) species and shade-tolerant crops? And, how to better understand the functioning of the greenhouse ecosystem, including combinations of crops and varieties, but also light, temperature, and implications for pest and disease management, and go from resistant crops to resilient cropping system? The development of a sustainable business model for these systems is important as well. In relation to breeding the following topics were identified:

- Establishment and screening of genebank collections to conserve and get access to the genetic resources needed for horticultural breeding programmes in existing and new crops – currently collections are only available for a limited number of greenhouse crops
- Application of novel breeding techniques to unravel the genetics of resistance and tolerance to biotic and abiotic stress factors
- Breeding for disease resistance, including vertical resistance, stacking of resistance genes; and search for new resistance mechanisms
- Development of mechanisms for disease diagnostics, especially for new diseases we may import from other parts of the world
- Study of interaction between species and functioning of the microbiome
- Development of a new role of greenhouses as a connection between producers and consumers in society.
- Cultivations of multipurpose crops requires breeding technologies as well as new business models

3.3 Nature-inclusive diary

Relevance and future of the system
The illustration of the nature-inclusive dairy production systems (Figure 3) was perceived by the participants as quite relevant for the future. The diversity in landscape and (non-productive) species, the grazing animals, the water management and the integration of nature and production appealed to the participants. On the other hand, some participants mentioned that feed crops should not be used for animal production when there could also have been grown something directly edible by humans. In addition, questions were raised about the economic and productive feasibility of such an extensive production system. The financial aspect/system was named to be one of the main barriers for the transition towards nature-inclusive agriculture. What makes the transition even more difficult, is that the design of these systems will be very context-specific. Also, the participants did not yet agree on how exactly to make the transition. There was discussion about the pace of the transition and whether it should start top-down (e.g., new policies) or bottom-up (e.g., actions of pioneer entrepreneurs).

Role of diversity in the system
Biodiversity was mentioned to be one of the core values of a nature-inclusive dairy production system. Biodiversity plays an important role in the resilience of a system against external stressors and to keep "harmony" within and between the different components and with the environment. Biodiversity was also mentioned to be important for healthy soil, nature, and the final product. The (genetic) diversity within livestock species should be utilized for selecting the right breeds and animals that fit into the system. The selection, however, might be very context-specific. One clear trait of the animals in nature-inclusive systems is to be able to turn lower and variable quality feed into high-quality product, since the illustrated production system is much more extensive than conventional dairy farming in the Netherlands currently is.

When focussing on selection and breeding of grasses and feed crops, the participants mentioned the importance of a plant to suit the local nature and soil type. The grass and crops should be suitable for the climate and for its purpose in the system. In addition, it is very important to know what the positive or negative effect of a plant is on the end-product (milk and meat). Although the system would be managed more extensively than conventional systems, the grass (mix) should be well digestible by the animals. To avoid the need for reseeding, plants should be bred for a long lifespan. On the other hand, some participants were critical on the role of plant breeding for nature-inclusive systems, since natural selection of species might be of more value in these systems. Moreover, the management of grasslands is crucial for increasing and keeping the diversity in the fields over years. However, optimal management for biodiversity might reduce the productivity and economic profitability. Lastly, some participants mentioned that fodder crops should only be used in animal production when it is grown as a fallow crop in a crop rotation to improve soil quality of arable land, and that the choice of plant species and plant characteristics should be optimized for that too.

Breeding goals and requirements
For animal breeding, it was mentioned that the genetic diversity between and within cattle breeds should be fully exploited for finding/creating the desired animal characteristics. Although the exact breeding goal and the prioritization of traits depends on the system and situation, some general desired traits are:

- Robustness
- Longevity
- Feed efficiency (for low quality feed)
- Health and disease resistance
- Ability to perform in systems with certain limitations (e.g., higher water levels of peat land)

To be able to breed for such traits, it is necessary to make them (easily) measurable, also by using novel technologies. Some participants see crossbreeding as a good strategy to breed animals suitable for nature inclusive production, although they mentioned that it is important to keep/conserve specific breed characteristics as well.

Access to genetic resources
In general, the availability of genetic resources suitable for nature-inclusive systems was not considered to be a limiting factor right now. However, for many (local) breeds there is limited attention and investments in breeding programs. Some (new) traits have never been measured before and, thus, also no breeding values are available on those traits. There is also limited evidence on interactions between species and between breeds within systems. It would require an investment to (know how to) obtain new and sufficient data, for instance by using novel technologies. Nowadays, most of the commercially available genetic material is primarily bred in the context of high-input systems, but breeding goals and data collection could also be adapted to alternative systems. Breeding companies could invest in a wider product portfolio for different types of production systems. However, commercial breeding companies are primarily driven by the market potential of their genetic products. Therefore, some participants emphasized the value of farm-specific breeding and a collaborative approach of farmers in similar production systems.

Key research topics
How to (practically) realise nature-inclusive dairy production on a large scale raised many questions and innovation ideas amongst the participants. Many of those questions were about financial aspects, knowledge sharing, effects of climate change, integral and location-specific approaches for studying farming systems. Some of the following topics were suggested specifically for animal and plant breeding aspects:

- Develop system-specific breeding goals and test animals for their performance in particular production systems
- Identify relevant (new) traits and measure these traits on a structural basis
- Determine the value of (combination of) traits that make some animals or plants stand out in nature inclusive farming systems
- Investigate symbiotic relationship of combinations of species (plants and animals) and the value of breed diversity at farm level
- Make better use of the material that is stored in genebanks to support breeding programs

3.4 Climate-smart forestry

Relevance and future of the system
The participants of the focus group perceived the illustration of the climate-smart forestry system (Figure 4) as relevant. Whereas some were less enthusiastic about the openness and limited structure of the system as indicated in the drawing, they appreciated that both above-ground and below-ground biodiversity were included, as well as the multifunctionality of the system. They questioned, however, if the transition towards such a diverse system is realistic.

Role of diversity in the system
A climate-smart forestry system needs (bio)diversity as a precondition for the functioning of the system. A forest that is rich in species can combine different functions of production and ecosystem services. Increasing diversity goes beyond just increasing the number of tree species, but needs to address all functional groups within the ecosystem and their interactions. A forest rich in diversity is more resilient against pests and diseases, with better spread of risks in case of a disease or pest outbreak. The participants also mentioned that mixed-species forests have better capacity to adapt to changing circumstances and are more resilient to disturbances, have higher productivity and provide for flexibility in management. Soil biodiversity is seen as an essential part of a resilient, climate-smart forest. In the context of a climate smart forestry approach, introducing new species with high drought tolerance and high litter quality could be beneficial. For the introduction of new diversity, it is also important to investigate potential risks, such as spread of invasive species and or new diseases and pests that come with the introduction of new species.

Breeding goals and requirements
Key traits remain growth, wood quality (stem straightness, branching) and phenological characteristics (including leaf development and flowering). New target traits for tree genetic improvement include wood quality properties suitable for innovations such as wood acetylation, frost tolerance, drought and heat tolerance, competitiveness, and carbon sequestration. In particular, selection for resistance against pests and diseases, both those that are already present and those that may arrive in the coming decades, has high priority. The question is how to find an optimum balance for all these different traits. In the face of environmental change and uncertainty related to climate change it is important to make use of the available adaptive genetic diversity within the current range of species, which is available through provenances from a range of different locations. These provenances may differ in their response to climate change, and they can be used for developing appropriate seed sourcing strategies. As trees have long generation times, they need to be able to adapt to changing circumstances and survive now and in the future. They also need to be able to rejuvenate, spread and coexist with other species. It is key to find the optimal combinations of species in climate-smart forestry systems, including species that are new to the Netherlands.

Access to genetic resources
Forest tree breeding merely focusses on species of high economic value. For most species tree improvement stops at selecting and testing provenances in trials and recommending the best-suited provenances for planting and selecting superior 'plus-trees' for seed orchard establishment. The next generation of seeds is produced by open pollination among these plus-trees. Access to seed sources from abroad for selection and testing as well for direct use as forest reproductive material (FRM) is of great importance.

In the Netherlands we face insufficient availability of genetic resources for some species, but at European level sufficient diversity is available. Participants mentioned that genetic materials selected in the Netherlands in the past may fit within climate-smart forest systems and may be evaluated again for future requirements, such as plasticity and climate resilience. We also face a knowledge gap whether foreign varieties and seed origins are suitable for our conditions. Knowledge and availability of appropriate foreign genetic resources could be increased by testing it in provenance trials and including it in the National list of recommended varieties and provenances of trees. New provenance testing should focus on new requirements and climate-related traits of local provenances as well foreign materials, including provenances originating from more Southern regions. It is important to establish more seed orchards within the Netherlands. Some key bottlenecks in relation to access to genetic resources and in particular forest reproductive material are: forest managers generally lack the network for access to suitable species and provenances outside of the Netherlands; international demand for forest reproductive material is huge; there is no constant supply of seed (mast years) and there are only a few nursery men specialized in forest trees, with focus on a limited range of provenances.

Key research topics
To strengthen climate-smart forestry systems both sharing of knowledge and communication have been indicated as key priorities. Unlocking (European) knowledge and addressing knowledge gaps in the entire production chain for planting at nurseries, cultivation techniques and lack of knowledge on species is necessary. Also, existing data such as keeping records of which provenances have been planted where, need to be easier accessible. To create support for intervention in forest management, communication within the sector, but also with society, needs to be improved. Empirical proof of the advantages and disadvantages of using local provenances or introducing more southern provenances is lacking. In the context of climate change, communication needs to address the appropriateness of local provenances versus the necessity of introducing new species and provenances.

In relation to increasing diversity within the system and tree improvement/breeding aspects the following topics came up in the discussion:

- Identify relevant species of the future forests (in 2050 and later) in view of climate change adaptation and mitigation and investigate how these species should be optimally combined
- Make better use of diversity in the forest system, including providing more genetic diversity for the system, and in terms of seed sourcing strategies and forest management
- Study provenance performance in relation to adaptation to climate change (local/autochthonous versus non-local/more southerly seed sources)
- Breed for disease resistance
- Make genomic research available for breeding

3.5 Agroforestry

Relevance and future of the system
A diverse group of stakeholders and experts in the field of agroforestry perceived the illustration of a diverse agroforestry system as quite relevant. Positive elements of the illustration were the mixed farming, the diversity of products, the soil life, the carbon fixation of the trees and other ecosystem services. Questions were raised about the amount of (hand) work, the economic feasibility, and the use of modern technologies. The illustration triggered some discussion about the combination of modern technology and biodiversity conservation in this system. In addition, questions arose about the scale of production that would be needed for economic feasibility.

Role of diversity in the system

Diversity is one of the main drivers for agroforestry systems. Participants agreed that diversity in the system could support the biological, economic, and social resilience of the production system. A high level of diversity in a system allows for a much higher level of risk spreading and adaptability to changing or unforeseen circumstances. Such a system does not necessarily focus on maximizing production of certain species, but rather optimizes the total production and ecosystem services. An important service of agroforestry systems is climate mitigation due to carbon sequestration of trees. Contribution of agroforestry systems to the landscape was also mentioned as an ecosystem service. Still, many participants had some concerns as well, as not all types of diversity might be accepted by the consumer or citizen. In addition, the more diversity there is in a system, the more knowledge it requires to manage it, so knowledge exchange should be supported. Legislation was mentioned to sometimes form a barrier for diversification of current systems.

Breeding goals and requirements

Selection of (combinations of) species and varieties for an agroforestry system should be based on soil type and other local circumstances. Synergies between the different species should be investigated and exploited in agroforestry systems to find optimal combinations of species and multiple functions. In that way, a range of primary and secondary products can be obtained from agroforestry systems, such as feed, food, and biomass. Breeding of all different crop, tree and animal species should focus on the combinations and interactions. In addition, growing and harvesting seasons of the different species should be in line with each other. Selection for compressed growing seasons could make it easier to combine different species. The crops in agroforestry systems should be shadow-tolerant, since trees will catch some of the sunlight. Animals in agroforestry systems should be bred for feed conversion efficiency of low and variable quality feed. Besides that, the animals should be resilient to stressors and have a long lifespan. Data collection is key for the breeding sector to work on these (complex) traits. The question was raised whether each farm would need their own breeding program, or that breeding can be done at a larger scale. Although the tree breeding sector is relatively small, a range of important traits were named by the participants apart from primary production and product quality: carbon sequestration, compatibility with rootstocks, a strong and well-structured rooting system, picking height of fruit and nuts, self-pollination, feed production for animals, water management characteristics and adaptation to machinery. Lastly, disease and pest resistance of all these different crop, animal, and tree species should be supported by breeding.

Access to genetic resources

Accessibility of genetic resources for agroforestry systems was experienced differently by different participants. For animal genetic resources, it was perceived that there was still sufficient material available within the Netherlands or abroad. It is more complex for the plant component. Some suppliers of genetic material are in a monopoly position and can, therefore, determine what material is available on the market. This may lead to a shortage of species, varieties, and locally adapted material suitable for agroforestry. One option to increase the availability of suitable genetic material is to re-examine old basic material, rejected in VCU (value for cultivation and use) testing in the past, taking new selection traits into account.

The main bottlenecks for accessibility of genetic material for agroforestry systems are the market forces and economic drivers, that only allow for large-scale breeding programmes that focus on a limited number of species and varieties. In addition, data collection, using new technologies, and research is needed to make the optimal genetics available. Practical farmers' knowledge and experience could support the selection of (novel) traits or species.

Key research topics

Agroforestry systems exist in many different forms and can incorporate combinations of many different species. The research agenda includes the following topics:

- Approaches for transforming current production systems into agroforestry systems
- Design of agroforestry systems, including combinations of species (plants, animals, trees) that work best
- Study on interaction between species
- Scalability of agroforestry models
- Business models for a range of agroforestry systems
- Tools to calculate the added benefits of an agroforestry system, both financially and environmentally

4 Key findings

4.1 Diversity between and within species

Enhanced genetic diversity (species, breeds) within production systems may improve the sustainability of systems, their resilience to environmental stressors, (long term) farm economics, climate mitigation and adaptation, and conservation of local biodiversity. One constant factor in the five systems that we described and discussed, is increased genetic diversity within but especially between species, of both cultivated and domesticated species, as well as the associated biodiversity (insects, mycorrhiza etc.). Increasing species diversity and genetic diversity between and within production systems may play a crucial role in the transition towards more sustainable and resilient forms of agriculture and forestry.

Species diversity within systems – more species, new species, and new combinations of species
Multiple species in a system allow for interactions and complementarity in species traits and functions. Increasing the diversity of species in the system is assumed to have positive effects on overall performance, resilience, resource-use efficiency, associated biodiversity and ecosystem services. These benefits probably occur in all systems, but the magnitude is dependent on the species choice, the combination of species, and the local context. To which extent species diversity is found relevant varies per system, and is determined by system boundaries, market opportunities and local circumstances.

Species combinations and complementarity are not random and to maximize the benefits of a species mix we need to understand the functional and structural complementarity between species. For instance, in mixed cropping and forestry we can investigate combining light-demanding versus shade-tolerant species, or shallow-rooting with deep-rooting species. In forestry systems, species with contrasting traits are assembled such as mixtures of broadleaves and conifers or broadleaves combined with understory. When increasing species numbers and identifying suitable combinations of species, there is a role for introducing new species or currently underutilized species. In intercropping systems, the use of new or underutilized crops such as 'forgotten vegetables' or perennial crops might be of particular interest when exploring successful species combinations, as this provides opportunities for crops that have a lower yield in a monoculture compared to some of the major crops. With respect to increasing species diversity on a temporal scale, crop rotations may also be extended with new or underutilized crops.

When choosing species or combinations of species or crops it makes sense to take climate change-related challenges into account or to try to realize synergy with other transitions, e.g., the protein transition. It is evident that different combinations of species in mixed crop, livestock, crop-livestock, forestry, or agro-forestry systems can play an important role in climate change adaptation and mitigation. For example, introducing new species in forestry systems should mainly bring in new properties which are relevant for climate adaptation (e.g., drought tolerance) and mitigation (carbon sequestration).

Typical for diverse systems is that multiple species are present, and that they interact in a positive way. The diversity of complementary species contributes positively to system functioning and performance. Multispecies systems may maximize beneficial interactions while minimizing competition. This is based on the concept that components in a system are not competing for the same ecological niche but are complementary. In all five systems that we identified and described, these interactions on all levels of species assemblies are seen as highly relevant. The interactions may include above-ground use of space at multiple levels, efficient use of different light levels, or below-ground complementary root systems to optimize water and nutrient uptake, but also interactions of the cultivated species with weeds or diseases and pests, or complementarity of different livestock, crop, or tree species within the system. The interactions with associated biodiversity (flora and fauna) and soil biodiversity were recognized as being highly important in all systems. Our knowledge on how to predict and optimize these interspecific interactions is still limited, especially when systems become more complex and diverse in terms of number of species and type of species.

Diversity within species
Optimal use of within-species genetic diversity is the basis for the breeding of new, improved, or well-adapted varieties. Breeding goals change over time when production system requirements change or because of changing consumer demands. For most systems, climate change will bring new threats and challenges that need mitigation and adaptation. First of all, this will require new genetic material that is adapted to different and challenging production environments. Crop varieties, animal breeds, and forest provenances with increased tolerance to higher and variable temperatures, heat, drought, frost etc. will be needed. Secondly, disease resistance/tolerance is highly valued as climate change may enhance outbreaks of new pests and diseases and allows them to move into new areas of production. For this reason, the relevance of adaptability and adaptive capacity was mentioned in focus group discussions for most systems. If crop varieties, animal breeds and forest populations need to cope with more variable conditions (e.g., in terms of temperature, water availability, feed quality) in the system, adaptability becomes more important than being adapted to optimal production conditions. This applies to crops, trees and animals in all relevant crop, livestock, crop-livestock, forestry, and agroforestry systems.

More genetic diversity in systems, in terms of different breeds/varieties or genetic diversity within breeds/varieties of crops, livestock or tree species, was also suggested as an interesting option, e.g., to capture some of the fitness advantages of hybrid crop varieties, or to take advantage of complementarity of breeds and to spread risks within the system. The relevance of genetic variation in relation to adaptive capacity within the system was perceived differently in the discussions on the five systems. This relates primarily to rotation times of the varieties, breeds and populations used. In forestry systems, above all a system with long rotation times, capturing enough adaptive genetic diversity within populations at the start is considered crucial. Mixed cropping, on the other hand, may adjust with every new cycle of the rotation, provided that new crop varieties are being bred that are adapted to the shifting conditions. Next to commercial breeding, other approaches were mentioned as well, such as participatory approaches[34] and local seed orchards. Furthermore, alternative options for exploiting genetic variation were suggested, such as using mixtures of (existing) varieties in mixed cropping mainly for improving biodiversity, combining different livestock breeds to make best use of the feed resources within the system, and mixed provenancing strategies in forestry systems, mainly to reduce the risks of climate change and pests and diseases.

Diversity at landscape level
The spatial scale is also relevant when optimizing production systems, and when combining species in and across production systems. The system may be optimized at plot level, farming system level, forest level, regional/landscape level, or even at higher levels. The regional or local context determines the limitations and requirements for a production system because production systems are affected by the surrounding environment and vice versa. For example, the farming system can have a positive or negative effect on the surrounding biodiversity, and alternatively, landscape elements or natural biodiversity can also affect the resilience or performance of the production system. Another example is that interaction between crops and livestock can be optimized at different scales, at field, farm or regional level, which can also influence the choice and optimization of species and species combinations at farming system level. And finally, risks of harvest failures or market distortions can also be mitigated at different levels, at farm level, or at regional level through collaboration or governance measures. Unfortunately, the landscape level is very difficult to include in breeding programs, as they need to cross and select genotypes that perform optimally in a defined system, not in a range of possible regional combinations. To some extent, participatory approaches that include local selection may include the landscape component, and this type of breeding and selection may have a relevant contribution for, e.g., agroforestry systems. For non-crop or undergrowth species or tree species of low economic value this may even be the only realistic option, as funds for larger breeding programs are lacking.

[34] Annicchiarico, P., Collins, R. P., De Ron, A. M., Firmat, C., Litrico, I., and Hauggaard-Nielsen, H., 2019. Do we need specific breeding for legume-based mixtures. Adv. Agron. 157, 141–215. https:/doi.org/10.1016/bs.agron.2019.04.001

4.2 Breeding goals and methods

New and more complex breeding goals
Breeding for crop monocultures or highly specialized animal breeds has focused on maximizing performance in single organisms in single-species, optimized stands with high farm management skills requirements, leading to highly productive yet specialized genotypes. Breeding of varieties or breeds optimized for agricultural systems with more diversity and multiple limitations and requirements becomes more complex for a number of reasons:

- Genotype by environment interactions, particularly in a multi-species setting, should be better incorporated in breeding program design
- The value of specific breeding goal traits for a particular species will be context-specific and will also depend on the breeding goals of other species within the system
- The breeding strategy must consider possible interactions between species
- New traits, relevant to induce or enforce beneficial interactions, should be added to the list of traits in the breeding goals
- The goal of increasing yield should be complemented by resilience-related and interaction-related traits, which are often more difficult to assess phenotypically
- More diverse systems offer opportunities for inclusion of new or minor crops, other forest species, or different combinations of livestock, crop, and tree species, for which little or no breeding has been done before and thus knowledge and tools may be lacking

For some systems, complexity is further increased because of the harvesting and use of the range of products. For instance, in mixed cropping it may be useful to align ripening of the grains and seeds of two or more crops in time to enable simultaneous harvesting, or it is desirable to use multiple parts of the plants, thus further diversifying the goals. Hence, species breeding goals are influenced by increased complexity and are determined by the complementarity of species.

More focus on local adaptation
The optimization of production systems is dependent on local circumstances, local conditions, and specific system requirements. Increased diversity of production systems can be expected when considering the multiple challenges, combined with a large diversity of local contexts. For breeding this means more attention to local adaptations and, for forestry, to incorporate models of the expected climatic conditions 50 or 100 years into the future. For future production systems the natural environment/landscape and local context will become leading, including climate- and biodiversity-related constraints/objectives. Consequently, the production system characteristics follow the environment, and breeding must follow the changing production system.

Improved technologies and new selection strategies
The above-mentioned challenges may partly be addressed by using improved technologies including automated phenotyping, genotyping, and artificial intelligence. However, it will also imply fundamental choices and new strategies to be developed about the context in which selection takes place. For livestock species, the features of the expected future livestock production environment determine the breeding goal and choice of breeds. Plant breeding programmes, which take into account Genotype x Environment interaction (GxE), may have to be expanded to S(pecies) x G x E x M(anagement) interactions. In a more diverse cropping system, some level of interactions needs to be included in the testing phase of the breeding programme, but it is impossible to test all advanced selections for all possible interactions. When complexity increases big data approaches are needed to combine large genetic and phenotype datasets. Plant growth modeling can help predict plant traits that affect both inter- and intraspecific interactions and their influence on crop performance[28]. Quantitative estimation of breeding values of crops or livestock is possible without necessarily understanding the exact underlying mechanisms. Various approaches will need to be combined to develop the more integrated and diverse breeding programs of the future.

4.3 Access to genetic resources for breeding

Different production systems have different diversity needs
A need for new species diversity and adapted genotypes is common across production systems. Breeding requires access to genetic resources for existing crops, new or minor crops, and livestock and tree species. The type of diversity that is required, however, varies across systems. In nature-inclusive dairy systems, we require for example new grassland and pasture species, as well as new varieties of currently used common pasture species, and well-adapted breeds of livestock for further improvement of the system. The forest production systems require, besides local and non-local provenances from currently common tree species, new tree and other species, originating from countries in drier and warmer climate zones. For increasing diversity in mixed cropping and greenhouse production systems, we foresee a demand for new traits within the current crops, and increased attention to combinations of currently dominant crops with minor crops and/or crops for specific purposes.

Screen existing genetic resource base in collections and breeding populations
For crops and tree species, existing collections of genetic resources, both *ex situ* (genebank collections, provenance trials) and *in situ* (natural stands of indigenous trees and shrubs) can be used as a source of new genetic material. However, they need to be screened for all relevant traits, and as we are looking for traits that have not yet been used within breeding programmes, it is not sure if such traits can be found in working collections of genetic resources within breeding companies, research institutes and genebanks. Especially collections of crop-wild relatives and currently underutilized species may need to be expanded to include sufficient genetic variation for traits that are important for the interaction with other species. The screening process itself is non-trivial, as it needs to be done in the presence of the potential partner species. This is because complementarity traits may partly be expressed in the partner species, which will not be revealed during screening of the target species alone. For livestock species, new breeding goals and traits may require screening of the diversity of existing breeds (*in situ* and *ex situ*), for their particular features.

Need for establishment of new collections
More diverse systems offer opportunities for inclusion of new or minor crops, but for most of these species only limited genebank collections exist at best, and if they exist, they have not been characterized for the breeding challenges ahead. Starting new collections and expanding existing ones is a very urgent challenge as natural ecosystems are declining, and species (and diversity within species) are being lost. Expanded collections should also include the wild relatives of the crop species of interest.

Lack of access to non-crop species for ecosystem services
Diverse production systems include a range of species that provide ecosystem services, either incorporated in the system (crop, livestock, forestry, agroforestry) or indigenous species of the native ecosystems next to it (field margins and hedgerows, surrounding natural elements). Genebank collections generally do not exist for native plant species, with some exceptions for endangered tree and shrub species for which specific measures have been taken. Nature managers sometimes have practical solutions to obtain the genetic resources they require for local nature development (e.g., transporting hay to move seeds between locations). These sources should also become available for more biodiverse production systems.

Regulation of global access to genetic resources – the Nagoya Protocol and the International Treaty
The global access to genetic resources at species, varietal and trait levels over the past three decades has changed substantially. For a selective group of food crops, the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) regulates access through a multilateral system. For many other crops and species, the Convention on Biological Diversity (CBD) through its Nagoya Protocol regulates Access and Benefit Sharing to genetic resources. International exchange of genetic resources for breeding and research is increasingly hampered since the adoption of the Nagoya Protocol. The access to new crop, livestock or forest genetic resources is increasingly bound to the current genetic resources available at national level, in breeding companies, on farm, in situ and in accessible genebanks. Hence, the current international legislation may also exert constraints on developing more diverse production systems and should be evaluated and improved in this context.

4.4 Availability of reproductive material and seed systems

Improved genetic material, new varieties or breeding stock originate from breeding programmes run by breeding organisations. The breeding sector can be divided in the key components breeding, multiplication, marketing, and delivery. Even though not fully applicable to animals and trees, we refer here to multiplication, marketing, and delivery of 'improved genetics' (e.g., breeding animals, crop varieties, improved forest reproductive material) as 'seed systems'. The characteristics and organisation of breeding programmes and seed systems vary between field crops, horticultural crops, grasslands and pasture, farm animals and tree species. Models vary from participatory/cooperative breeding programmes to institutional and industrial breeding programs. Particular species arrangements in production systems are linked to a diversity of breeding and seed systems, each with their own features.

Seed systems and industry configurations vary among production systems
The access to seed, breeding animals, reproductive material or genetic resources of crops, livestock and trees depends on the seed system, structure of the breeding sector and industry configurations. The relationship and distance between farmers/end-users of breeding material and the providers of breeding material is also relevant. Farmers can join cooperative or participatory breeding programmes or can be considered as end-users of improved genetic material. The time dimension (duration from breeding to seed use, and frequency and efficiency of new genetics becoming available) and space (scale in which they operate, varying from global to more regionally bound breeding and seed systems) are also relevant. Development of animal breeds, field and horticultural crop varieties, and to some degree varieties for grasslands and pastures, is dominated by specialized breeding companies. For the major species of crops and mainstream livestock breeds, it is primarily multinational companies that run the breeding programmes and seed systems, while for vegetables crops, as well as ornamentals and upcoming crops such as biobased crops and protein crops, there are also many small- and medium-sized (SME) companies. In addition, there are also active national networks of breeders, breed societies and NGO's that play an important role in the conservation, breeding and the promotion of mainly local breeds and varieties. For forest trees at European level, and this applies also to some extent for livestock and crops, breeding and seed systems are structured in regionally, but even more nationally bound public-private partnerships or managed by networks of breeders. Forest genetic resources research ('tree improvement and breeding') is driven by public or semi-public research organisations that are linked to public-private bodies engaged in multiplication, marketing and delivery of those species and genetics ('tree seed system'). It is expected that forest tree breeding will mainly retain a national or regional focus as improvement and breeding is oriented towards providing improved material for specific bio-geographic zones, so-called breeding zones based on soil and climatic criteria. However, increased concentration of players and globalization in for example the wood and paper industry and a changing climate may result in greater emphasis on multiregional collaboration regarding (pre) breeding and use of improved FRM.

Opportunities, boundaries and lock-ins in breeding and seed systems
The way breeding and seed systems are structured, including the business models that drive them, create both opportunities but also boundaries to the way breeding can respond to accommodate greater diversity in breeds, varieties, species, and groups of species. It is relevant to characterize those business models, identify opportunities and boundaries and lock-ins, including variations between private/closed and more public/private and more open seed systems, cooperative breeding programmes and participatory breeding approaches, and explore the development of pathways to restructure or create incentives for the breeding and seed systems to overcome critical boundaries and promote diversity. Another critical aspect is the degree in which intellectual property regimes foster the private investment in breeding and allow for broadening the genetic resources base for making more diversity available for production systems.

A more conceptual feature to be considered when exploring how breeding can contribute to and respond to the increased demand for diversity in production systems is related to aspects of time and space. Regarding time, the duration of breeding and seed systems varies between production systems. The lifespan of vegetable varieties in greenhouse horticulture is short, production and marketing of for example new tomato or cucumber varieties is rapid and efficient. For field crops, grassland and pasture species, and for example livestock such cycles are longer, but still, they remain shorter than the cycles of decennia that characterizes tree breeding.

Breeding and seed systems operate primarily global (plants and animals), to more national and regionally bound markets (trees and animals). Business models of individual (multinational) breeding companies largely determine how much diversity will be available on the market. Strategies of breeding companies are determined by expected turnover and profit, combined with geographical, climate and specific market demands. Hence, the interest or ability of the established breeding sector to respond to changed demand for enhanced diversity may be limited. Additional or different public, public-private or private initiatives may be needed to foster access to more species and genetic diversity in future production systems.

4.5 Communication and knowledge exchange

Making optimal use of the genetic diversity in crops, livestock and forestry species and long-term conservation of genetic diversity for future research and breeding is a prerequisite for the transition towards more resilient and sustainable food systems and forestry. Addressing multiple challenges and adaptation to local circumstances will result in a larger diversity of future production systems, and therefore require more diversity in species, breeds, and varieties. The awareness and knowledge are limited among stakeholders and in society at large about the relevance of species and genetic diversity within systems, the complementarity of species, and the need for continuous development of well-adapted breeds and varieties. A paradigm shift is therefore needed in agriculture and in society to acknowledge the relevance of an integrated systems approach dealing with many challenges and societal values simultaneously.

To deal with these challenges, the breeding sector plays an important role in developing improved, well-adapted genetic material for a larger diversity of species and systems. This requires a close exchange of information between the breeding sector and farmers. The business models of the breeding sector may need to be adapted and their product portfolio expanded. New public, private or public-private initiatives are needed to invest in research and breeding programmes for the currently underutilized species, breeds, and varieties.

Good communication and knowledge exchange outside the breeding sector might be just as important to implement the use of a wider diversity of genetics in production systems. To reach the aforementioned vision of future production systems, it is essential that new research and developments are shared across countries, sectors, institutes, researchers and farmers, to embed the knowledge in practical solutions, and to stimulate its use. Farmers should have more involvement in research, and should help to set the research agenda, to create more support and stimulate the adoption and implementation of new innovations. In addition, knowledge exchange between farmers and between farmers and third parties was named to be essential for the transition towards more sustainable agriculture. Lock-ins in policies and regulations should be tackled to facilitate further diversification in agriculture and forestry.

Lastly, it is necessary to sensitize and communicate to consumers why certain sustainability choices are made, to stimulate a demand for sustainable products, and to justify the added value paid for it. In addition, to stimulate appreciation of more sustainable and resilient production systems, embedding production systems in the landscape is important. Consumers and society (in particular, the youth) should regain appreciation and awareness of where our food comes from, be informed about sustainable and resilient food systems and forestry, and the important role of species and genetic diversity.

5 Research priorities

We started the study with two key research questions:

- Which (combination of) species, varieties, breed and genetic diversity in crops, livestock and forest are needed or create added value to future production systems?
- What opportunities and challenges arise for the crop, animal and forestry breeding sectors

Based on the analysis and focus group discussions we have formulated the following overarching strategic research questions that should be addressed in future research:

- Increased species and genetic diversity in breeding: which traits and interactions are relevant?
    - New combinations of species: what kind of features and functionalities are important?
    - What are the benefits of breed diversity or heterogeneous varieties within production systems?
- How to increase access to genetic resources for breeding, and how to enhance the availability of reproductive material for a range of systems?
- Adaptability and resilience: how to define and to implement in breeding programmes?
- How to apply new breeding methods, new technologies and different breeding approaches?

Increased species and genetic diversity in breeding: which traits and interactions are relevant?
Improving the resilience and sustainability of specific production systems may benefit from introducing new (combinations of) species into the system. Considering a range of production systems, based on the local context, the number of possibilities would seem endless. What are promising combinations of species, and how can the benefits of specific combinations of species be assessed systematically, taking into account the already dominant species in agriculture and forestry, but also local gene pools and underutilized/minor species, breeds, and varieties. In addition to species- or breed-specific features and functionalities, complementarity and avoidance of competition are important aspects. For example, in mixed cropping systems, crop species should not compete with each other, but they still need to outcompete weeds. In agro-forestry, the resilience and long-term sustainability of the whole system will benefit from specific combinations of tree, crop and/or animal species, depending on the local context.

A large diversity of future production systems will require tailor-made breeding goals for each category of production system or production environment. Breeding goals should prioritize all relevant (new) traits, for relevant species within the production system. More genetic diversity within systems (between and within species) will also increase the complexity of determining breeding goals. Across agriculture and forestry production systems, adaptability, tolerance or resistance are considered as important traits, next to productivity. For example, in nature-inclusive dairy systems, grass diversity in pasture and variable feed quality requires robust livestock breeds which are well adapted to more variable or marginal production environments. Climate-smart forestry requires the identification of traits that support the adaptive capacity of forests over a longer time period.

Moreover, different or heterogenous breeds/varieties within species (different breeding goals) may also have added value in a particular production system. In addition to species and breed diversity, heterogeneity in breeds/varieties within production systems may for example be beneficial for disease management in crop production, or for making optimal use of the feed resources available in livestock production.

By increasing the number of genotypes within a crop, animal or tree species, and the number of species in a production system, and by introducing new species into the system, the complexity of the number of possible interactions explodes. Clearly, not all possible combinations can be experimentally tested. If we have a good notion of which types of interactions are relevant, and which traits contribute to these interactions, we can make informed choices and breeding programmes may become much more effective It is therefore relevant to develop a systematic approach to be able to identify a set of interactions that we want to improve in the new production system, and which traits in the crops, breeds, trees need to be measured to be able to predict or test improved interactions.

The research question may draw knowledge from farmers experiences or from crop growth, ecosystem, or production system-specific models. Complementarity and interaction play both at the level of variation within a species (multiple varieties, heterogeneous varieties) as among species, above- and below-ground, and temporal).

How to increase access to genetic resources for breeding, and to enhance the availability of reproductive material for a range of systems?
Existing genebank collections, *in situ* populations or breeding populations may be screened for new traits. New opportunities will arise for breeding, based on enhanced genomic and phenotypic characterization of genetic resources in/for a range of systems, including underutilized species, breeds, or varieties. Screening of genebank collections may also indicate that more diversity is needed that is not yet captured in the genebank collections, e.g., of currently underutilized species.

Increasing diversity between and within production systems will require broadening of the genetic product portfolio available for farmers and end-users. Expanding publicly available genebank collections is a task for governments. Breeding companies' business models and the seed systems that multiply and distribute the material need to be adapted accordingly, which is a task for the formal seed sector and - complementary - through participatory and cooperative approaches. Lock-ins and limitations need to be identified and solved by private and/or public interventions.

Adaptability and resilience: how to define and implement in breeding programmes?
The increased genetic diversity within systems is meant to increase the resilience of the production system. That means that adaptability and resilience should also be key factors to evaluate when breeding varieties and breeds for particular systems – and that for instance productivity or maximum yield is not necessarily the best or only criterion, but also stability of yield in different environments and over time. There is a need for better methods and tools to assess traits related to resilience and adaptability. How can we develop criteria for which to select, that can be determined relatively efficiently and that capture a large part of the contribution of a genotype to the resilience of the system? This is a joint task of research institutes and (private) breeders.

Crop and tree breeding should further focus on mechanisms of disease resistance. For mixed cropping systems intercropping features will contribute to resilience and adaptability. Intercropping features are often complex traits, that require new breeding approaches and strategies. Animal breeding should focus on breeding of robust animals, which are either adapted to specific production systems or that fit a range of production environments.

How to apply new breeding methods, technologies, and breeding approaches?
The increased complexity of diverse production systems is a challenge that requires more data and new approaches to use them. How can automated measurements and analysis of data on a multitude of traits, their interactions and environmental factors help to manage the increased complexity, and assist breeders to make the best decisions? For example, novel analysis tools are needed to unravel the genetics of resistance and tolerance to biotic and abiotic stress factors and to better understand disease resistance mechanisms.

Breeding for a diversity of production systems should take advantage of different breeding approaches. In crops, breeding programmes would clearly benefit from the use of new breeding techniques to speed up breeding. Genomic selection is a powerful methodology in both plant and animal breeding, and participatory breeding approaches, directly involving (networks of) farmers in the breeding program, are relevant in both plant and animal breeding.

In conclusion
Multiple challenges and transitions that are needed in agriculture and forestry require an integrated approach. Context-specific optimization of production systems, which have to deal with multiple challenges, will result in a larger diversity of resilient and sustainable future food production and forestry systems, and increased diversity within production systems. Crop, tree, and livestock species diversity, and the genetic diversity within species, is the basis for the functioning, the resilience and productivity of production systems. Increasing genetic diversity within systems also implies many interactions and increasing complexity.

Further strategic research in the context of crop, tree and livestock breeding should particularly investigate the relationship between wider genetic resources use, beneficial species/breed/variety interactions at the level of functional interactions, and how these may contribute to the resilience of production systems (Figure 6). The increased (data) complexity must be managed in research and breeding, making best use of new technologies, methods and breeding approaches. These are all issues within the domain of WUR research. Implementation of the findings poses challenges for partners and stakeholders of WUR in the breeding and seed sector such as breeding companies, public breeding institutes and participatory networks, seed and plant material suppliers, as well as farmers.

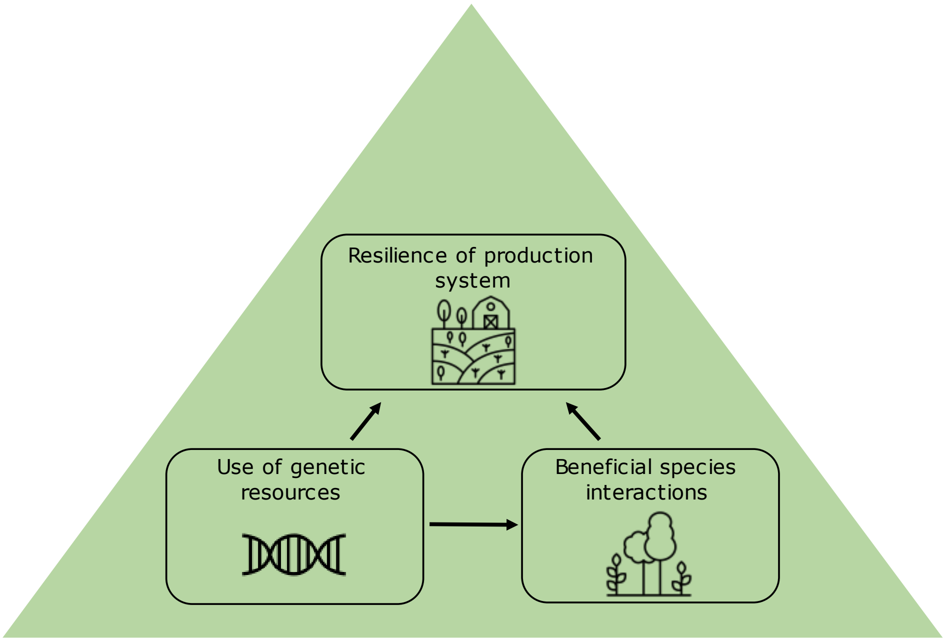

Figure 6 *A triangle for improving resilience in agricultural systems.*

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
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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.