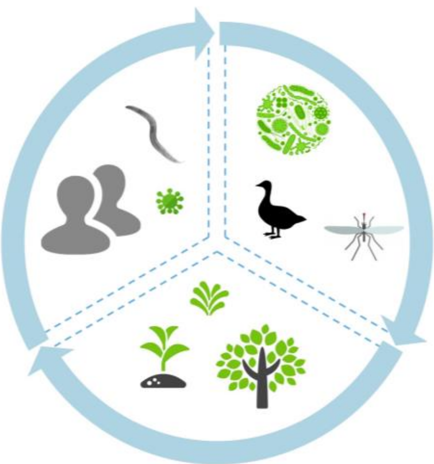
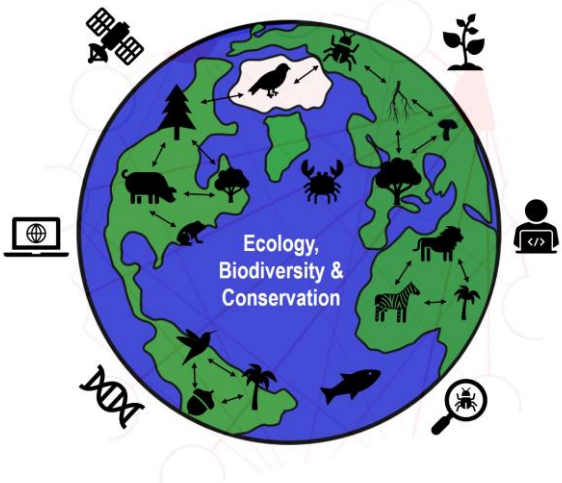
Peer Review 2021

Graduate School Production Ecology and Resource Conservation

PE&RC

The C.T. De Wit Graduate School PE&RC
PRODUCTION ECOLOGY & RESOURCE CONSERVATION





Summaries and Case Studies

Self-evaluation document

Graduate School for Production Ecology and Resource Conservation

(PE&RC)

Summaries and Case Studies

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1. Summary PE&RC

The Graduate School PE&RC is a collaborative research and PhD training community. Its main aim is to develop, coordinate, and facilitate a world-leading training programme for PhD-candidates and post-doctoral fellows within the field delineated by our scientific mission to "**Understand the functioning of natural and managed ecosystems, to improve the quality of life**".
Members of the graduate school are PhD-candidates, postdocs, and scientific staff of Wageningen University, Utrecht University, University of Amsterdam, Vrije Universiteit Amsterdam, Radboud University Nijmegen, Netherlands Institute for Ecology, and Naturalis Biodiversity Centre. The Graduate School PE&RC is coordinated by Wageningen University.

The PE&RC research challenges are to:
- Understand the complexity of ecosystems and derive unifying concepts at various spatial and temporal scales;
- To assess how these concepts vary between different spatial-temporal scales and different levels of biological organization and complexity;
- Develop quantitative approaches in which observation, experimentation and modelling are combined and different scales of observation are quantitatively connected and synthesised;
- Integrate the different required/relevant disciplines and design novel production and land use systems in relevant temporal order and spatial configurations.

The collaborative research programme of PE&RC within Wageningen University emerges from the more disciplinary questions that each research group within PE&RC works on and which are grouped in four overarching research themes.

There are four research themes:
(1) Re-design of agroecosystems
Mission: to assess and design sustainable agroecosystems focused on the provision of multiple ecosystem services, resilience capacity and equitable management of natural resources contributing to global food security, resource conservation and societal well-being.
(2) Ecology, biodiversity & conservation
Mission: to generate insights into ecological processes and interactions, and use these to design effective strategies for the protection, restoration and sustainable use of ecosystems and biodiversity.
(3) One Health
Mission: to explore ecological, evolutionary, and molecular processes to improve the health of organisms and the environment they live in.
(4) Data and engineering science
Mission: to provide the methods, technologies and tools to solve complex societal problems through integration of novel data acquisition tools, quantitative and qualitative modelling with domain knowledge.

Themes offer unique opportunities for scientific development in response to society's grand challenges. PE&RC with its general focus on sustainability, land use, food production, biodiversity and research to mitigate and adapt to climate change, as well as excellent research in developing countries, is well placed to take advantage of this structure.

Since interdisciplinarity and societal relevance of research will increase in importance during the ongoing decade, the development of the themes must be viewed as an opportunity for Wageningen University to take the lead in these research areas. There is a need to transform science and how it is carried out to successfully address these grand challenges in an interdisciplinary approach.

In the coming period PE&RC aims to strengthen the organisation of its themes through making their roles more explicit. This will be done for example through stimulating theme activities, giving themes a larger role within the PhD programme, and by stimulating shared staff hires within a theme. This strategically positions PE&RC for the transition that the scientific world is making with focus on diversity, team science, and doing science that generates impact.

Research Theme

Re-design of agroecosystems

2. Theme Re-design of agroecosystems

2.1 Summary theme Re-design of agroecosystems

Agriculture is at a crossroads and solutions are needed to ensure that present and future systems can produce food in sufficient quantity and quality for the growing population. Yet, agroecosystems must provide more than food, including a wide variety of ecosystem services, while contributing to biodiversity conservation and ensuring resilience in the face of shocks. These multiple challenges call for combined efforts from researchers and other stakeholders to (re-)design sustainable agroecosystems to facilitate the transition to a more circular and sustainable agriculture. The successful re-design of agroecosystems entails a deep understanding of plant and ecosystem functioning and societal demands as well as the co-creation of feasible management strategies considering contrasting (and changing) socio-ecological contexts. Solutions for redesign are complex and can differ widely depending on local conditions and socio-economic factors (e.g. challenges faced differ widely between small scale farms in Africa, glasshouse horticulture in the Netherlands or grain producers in Latin America) but there are also synergies and shared lessons to be learned. Research in this theme addresses agricultural issues in a wide variety of agro-ecological and socio-economic settings across the globe putting us in an ideal position to learn these shared lessons.

Our mission is to assess and design sustainable agroecosystems focused on the provision of multiple ecosystem services, resilience capacity and equitable management of natural resources contributing to global food security, resource conservation and societal well-being. Therefore, the theme seeks fundamental understanding of the crop requirements, drivers and mechanisms of agroecosystem functioning as well as the development of knowledge and tools that contribute to re-designing production systems in multifunctional and dynamic landscapes. Our research strategy integrates different spatio-temporal levels of analysis, from crop genotypes, fields and farms to global level. Data is obtained from field and laboratory experiments, existing databases and real-life farming systems across the globe to derive actionable knowledge that can be useful to adapt and transform current agroecosystems. A strong focus is given to crop-soil-water relationships and agrobiodiversity to advance the understanding of dynamic interactions among system components as well as impacts of land use and management on soil quality, farm performance, and ecosystem functioning. Our mission is addressed by four research lines: 1) crop performance and breeding, 2) agronomic and technological innovations, 3) ecological processes and diversification, and 4) adaptation and transformation pathways. Our research provides grounded, quantitative and qualitative analyses and models which enhance understanding and support responses to global challenges through the understanding and design of sustainable farming systems. Collaboration with a wide variety of scientific institutes and societal groups ensures that a wide range of topics and realities are covered. Research outputs are published in highly cited journals, but also influence policies and societal groups.

The future of the research theme is promising due to the broad scope, high quality and impact of the work currently developed. The size (nine chair groups) and combination of expertise of the theme put us in an ideal position to make steps in research on ecological redesign that cannot be made by individual chair groups or through bilateral collaborations alone. In the first year of the existence of this theme, we have started to capitalize on this through, for example collaboration in the development of farm of the future, the crop diversity systems experiment, NPEC, and the Wageningen Photosynthesis Centre and many other efforts mentioned in the report. The challenge for the next five years will be to develop a coherent research strategy that builds on our strengths and helps us tackle the issues we deal with while simultaneously maintaining a healthy and diverse working environment for employees.

2.2 Case Studies theme Re-design of agroecosystems

Case study 1: *"Learning from the future" - The Global Network of Lighthouse Farms*

Description

The Global Network of Lighthouse Farms, or GNLF, serves as a global outdoor laboratory on future farming systems by bringing together existing "successful exemplars of disruptively innovative farming systems (i.e., lighthouse farms) that are proving to be economically, environmentally and socially sustainable and as such already rising to the multiple challenges of a shared future that is food secure, nutritious, sustainable and resilient" (Valencia et al., *under review*). These farm and foodscapes form a mosaic of solutions and innovations for a range of soils, climates, cultures, and local condition.

Currently, the GNLF includes twelve farms that have already uniquely redefined at least one dimension of sustainability highlighting a transition pathway towards a sustainable foodscape, allowing for in-depth investigations of specific topics. Each of these lighthouses is a network on itself, an entry point to a foodscape, including connections to over 70 research institutes and universities, and local decision-makers and communities that support the establishment of locally embedded research agendas.

1. **Circular economy** (Latvia). AS Ziedi JP is an example of circular economy, where one segment's products or waste serve as raw material for other business segments.
2. **Climate Smart Village** (Cauca, Colombia). The CGIAR's Research Program of Climate Change, Agriculture and Food Security along with a local NGO are pioneering the Climate Smart Village approach to support rural communities to become more resilient to climate change.
3. **Community-based land governance** (Atsbi catchment, Ethiopia). Exemplifies how community-based land governance has successfully reversed land degradation in a semi-arid environment.
4. **Regenerative agriculture** (Murcia, Spain). A beacon of regenerative agriculture in the border of a desert.
5. **Organic urban agriculture** (Havana, Cuba). A model of cooperative production to manage diverse cropping systems in a large urban garden.
6. **Organic farming and vermiculture** (Absdorf, Austria). A frontrunner in advancing vermiculture and vermicomposting, this organic farm applies low-tillage methods to maintain and improve soil health.
7. **Low carbon beef** (Lands at Dowth, Ireland). Production of low carbon beef and lamb by developing a dynamic, healthy ecosystem.
8. **Community, energy production and biogas** (Hyvinkaa, Finland). A multi-enterprise network producing local organic food while also recycling nutrients and producing renewable energy.
9. **Strip cropping farming** (Netherlands). Demonstrating that large commercial farms can also be diverse and organic, this farm—the largest organic farm in the Netherlands—is experimenting with mixed cropping systems, including strip cropping.
10. **Complex rice systems** (Indonesia). Complex rice systems that combine rice production with the cultivation of fish, azolla and ducks, creating resilient system.
11. **Regenerative agroforestry and silvo-pastoral systems** (Brazil). This large farm is scaling regenerative organic agriculture by designing and implementing farming systems (agroforestry and organic grain crops) that sequester carbon from the atmosphere and restore biodiversity while simultaneously being highly productive and profitable.
12. **Community-wide organic farming** (Sikkim, India). Exemplifies how public policies may support the transition of an entire region to organic production systems.

A novel approach: "Learning from the future"

Realizing radically progressive yet attainable futures requires novel approaches to imagining, anticipating, and planning that explicitly include disruptive, heretofore unexplored solutions. The GNLF makes possible a new approach to search for solutions beyond the boundaries of the current known solution space: rather than starting from the problem—the status quo locked into a past solution space—and trying to work out a solution ("learning from the past"), the GNLF allows us to "learn from the future" by starting from a vision grounded on existing exemplars and then elucidating the transition pathways to attain those farms and foodscapes (Figs 1 & 2; Valencia et al, under review).

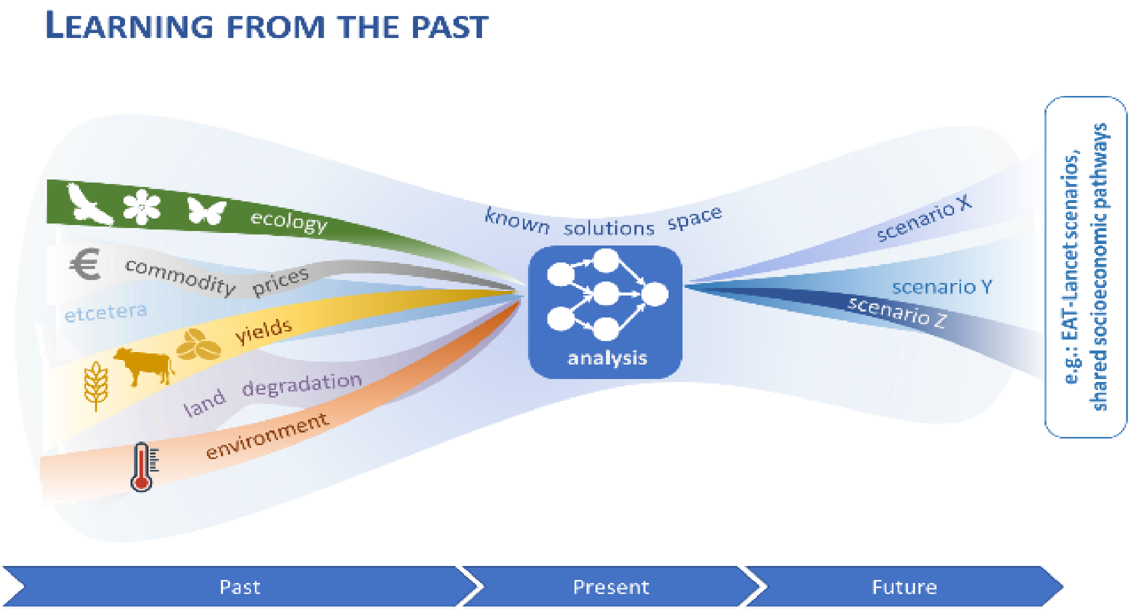


Figure 1. *Learning from the past: research to transition pathways commonly relies on relationships that have been observed in past and present food systems.*

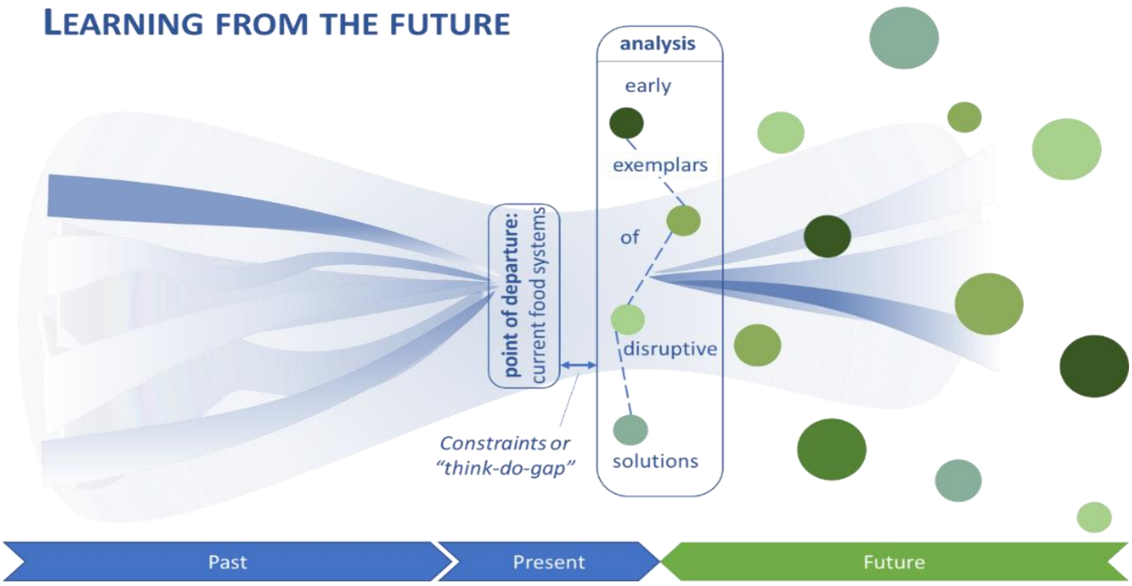


Figure 2. *Learning from the future: understanding and mainstreaming early exemplars of disruptive solutions.*

Research agenda: Towards a great transformation in food systems

The GNLF is driven by key fundamental questions that address the "great transformation" needed in our food systems: What are attainable, yet radical visions for sustainable food systems? What are the transition pathways that can get us there? What are the common ingredients across the diversity of context-specific solutions? (Fig 3). Through co-innovation and in a transdisciplinary approach, the GNLF brings together researchers and students with local communities to identify and understand barriers to transformation, and either chart a path to removing these, or iteratively 'redesign the lighthouses' to be compatible with local decision making.

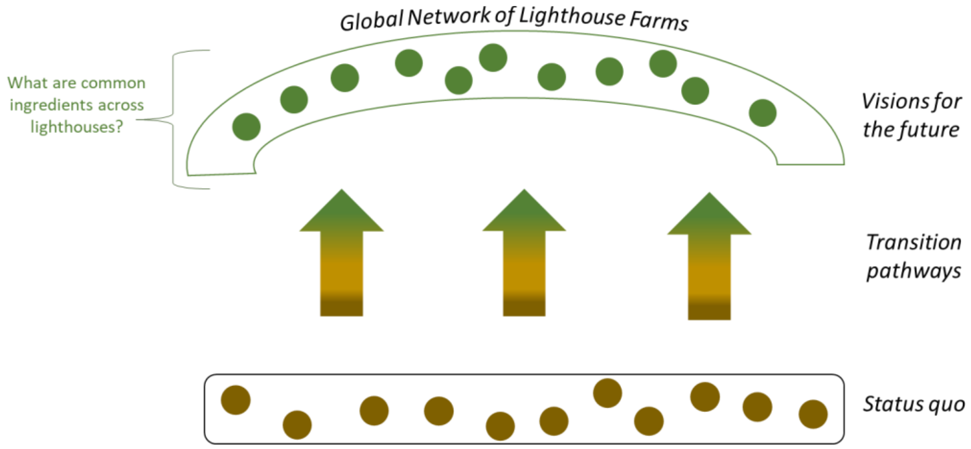


Figure 3. *The Global Network of Lighthouse Farms brings together disruptive exemplars in food and farming systems from around the world that have found radical solutions to address current sustainability challenges. These lighthouse farms illuminate diverse visions for sustainable futures, and transition pathways from the status quo to sustainable futures.*

While individual lighthouse farms may be continuously evolving and as of yet be imperfect, as a network they have unveiled the diversity of context-specific solutions available, which allows for the study of the reconfigured trade-offs and synergies that these farming systems share as common ingredients. One such common ingredient across lighthouse farms that we found outside the known solution space of most scenario models is the successful harnessing of biological complexity to unlock synergies between farm elements to co-deliver provisioning, supporting and regulating ecosystem services. The scale at which complexity is managed differs between lighthouse farms and ranges from synergies between crop species and varieties at plot scale in strip-cropping in the Netherlands (Ditzler et al. 2021) and multi-species grasslands in Ireland (Grace et al 2019), to synergies between guilds in complex rice systems in Indonesia (Khumairoh et al 2018) and in successional agroforestry in Brazil (Santos et al 2019), all the way to synergies between farm enterprises (crops, livestock, bioenergy production) at farm (Koppelmäki et al 2019) or regional scales (Koppelmäki et al 2021) in Finland. This harnessing of complexity is a knowledge-intensive process that demands significant inputs of management and collaboration: a constraint for which the lighthouse farmers have found an equally diverse range of solutions.

Scientific and societal impact

Scientific papers, research and education

Current and past research led by the Farming Systems Ecology group (FSE) at the different lighthouses has produced a variety of scientific publications including those on pixel cropping (Ditzler et al., 2021), nested circularity (Koppelmaki 2019, 2021) and on Complex Rice Systems (Khumairoh 2018, 2021). In 2019, the Global Network of Lighthouse Farm took central stage, literally, at the inaugural speech of Prof. Dr. Rogier Schulte. We have further prepared a synthesis paper in which we analyse the 'learning from the future' approach drawing from both the GNLF and two other international initiatives (Agroecological Lighthouses and Seeds of Good Anthropocenes) that have developed independently (Valencia et al., *under review*).

In 2019, we secured funding for a Marie-Curie Industrial Training Network named Heartland Project at the lighthouse farm 'Lands at Dowth' in Ireland, which includes funding for five PhDs studying how economically and environmentally sustainable ruminant livestock products of enhanced nutritional value can be developed through a pasture-based production system while complementing soil, sward, animal, environment and ultimately human health. We also have one PhD student investigating the links between biological complexity and soil-based ecosystem services in agroforestry systems at 'Rizoma Agro', the Brazilian lighthouse farm, funded by a Swiss philanthropical organisation.

The GNLF plays a strong role at the educational program of Organic Agriculture and Agroecology at Wageningen University. Not only do we introduce the lighthouse network in lectures on learning about transforming foodscapes, we also use video material including Virtual Reality to 'bring the lighthouse farms into the classroom'. Structurally we provide a guest lecture for the course *Business cases in agri-food entrepreneurship* using lighthouse farms as important sites to learn from the future; and for the course *GIS for Society*, where we provide a workshop on the use and application of Virtual and Augmented Reality in education. We further encourage students to engage, through either an internship or thesis, with the lighthouse farms while building on past research conducted by previous MSc and/or PhD students. This also allows for participatory research designs where the farmers have an important role of the research questions asked. As such, the outcomes are of benefit to the farmers as well.

In addition, the GNLF collaborated with the WBCSD to co-host an event that aimed to elevate producers' s voices during their Liaison Delegate Meeting. This dialogue was held in advance of the United Nations Food Systems Summit to bring the perspective of farmers to the boardroom; it resulted in a series of blogs and concrete recommendations for different stakeholders in the global food system. The collaboration is further fostered through a co-supervised MSc student, and aims to connect research within the GNLF research with WBCSD membership.

European Commission: Mission area soil health and food

The European Commission has defined five missions within the context of the Horizon Europe programme from 2021- 2027. 'Mission area: soil health and food' aims to provide a tool to raise awareness on the importance of soils in restoring health for people and planet, as is defined in detail in their first report 'Caring for Soil is Caring for Life.' As a key member of the Mission Board, Alfred Grand, the Austrian Lighthouse farmer, proposed that the European Commission adopt the concept of Lighthouses, and respectively it is a concept that is now included at the core of the mission. As is stated in the summary (Caring doe soils is caring for life), *This interim report sets out the vision and the blueprint to reach this ambition through a combination of research and innovation, training and advice, as well as the demonstration of good practices for soil management using "Living labs" and "Lighthouses".* Considering that this report is a fundamental framework for how R&I will be deployed in the field of sustainable agriculture, the concept of Lighthouses is now also found in other Commission documents, such as the Organic Action Plan. Furthermore, the framework will be triggering the development of new lighthouse networks, who have begun to reach out to GNLF as the "North Star" for guidance on how to work with farmers, what criteria to use to define sustainability, and what lessons can be learned from the existing network.

Selected popular science outreach

In the book '10 Miljard Monden' (10 Billion Mouths) on how to feed the world healthy and sustainable food in the future, a chapter on the lighthouse network presents three lighthouse farms: complex rice production in Indonesia, stripcropping in the Netherlands and cooperative farming in Cuba.[1] The chapter further shows how complexity, cooperation and innovative use of technology are part of the common ingredients highlighting transition pathways to sustainable foodscapes. A different Lighthouse Farm features every six weeks in our own Lighthouse Farms Network column in the Irish Farmers Journal. Besides the website where more academic and popular science publications are listed (network resources), the GNLF showcases its farms and accomplishments on various social media platforms including Facebook, Twitter and Instagram.

Next steps

As our research agenda suggests, by learning from the future we aim to identify transition pathways to a sustainable future. An interdisciplinary approach is needed to accomplish these goals, therefore our next step is to prioritize collaboration with other groups within WUR such as Rural Sociology, Business Management and Organisation and Sociology of Development and Change from the Social Sciences, but also with Animal Production Systems and Soil Biology from Animal and Environmental Sciences respectively. In addition to strengthening collaboration within WUR, partnerships with other universities and research centres are crucial to reach our objective of transdisciplinary research and dialogue. Key to this, noticeably, is the constant interaction, feedback and input of the lighthouse farms and their different sets of networks. The central role of the lighthouse farms as global classroom and laboratory, while being administered by FSE, will be ensured by continuous interaction with research through students and researchers from within and also beyond WUR, including other partners and initiatives. Eventually, in order to reach the wide spectrum of solutions to be represented by twenty successful exemplars of disruptively innovative farming systems that are proving to be economically, environmentally and socially sustainable, we hope to invite eight new lighthouse farms to join the network in the next three years.

Key scientific publications

Ditzler L, van Apeldoorn D, Schulte R P O, Tittonell P and Rossing W A H (2021). Redefining the field: A conceptual framework for mobilizing three-dimensional diversity on the arable farm, with an application Eur. J. Agron.
Grace C, Lynch M B, Sheridan H, Lott S, Fritch R and Boland T M (2019). Grazing multispecies swards improves ewe and lamb performance Animal 13 1721–9
Khumairoh U, Lantinga E A, Schulte R P O, Suprayogo D and Groot J C J (2018). Complex rice systems to improve rice yield and yield stability in the face of variable weather conditions Sci. Rep. 8 14746 Online: http://www.nature.com/articles/s41598-018-32915-z
Khumairoh, U., Lantinga, E. A., Handriyadi, I., Schulte, R. P., & Groot, J. C. (2021). Agro-ecological mechanisms for weed and pest suppression and nutrient recycling in high yielding complex rice systems. Agriculture, Ecosystems & Environment, 313, 107385.
Koppelmäki K, Helenius J and Schulte R P O (2021). Nested circularity in food systems: A Nordic case study on connecting biomass, nutrient and energy flows from field scale to continent Resour. Conserv. Recycl. 164 105218 Online: https://linkinghub.elsevier.com/retrieve/pii/S0921344920305346
Koppelmäki K, Parviainen T, Virkkunen E, Winquist E, Schulte R P O and Helenius J (2019). Ecological intensification by integrating biogas production into nutrient cycling: Modeling the case of Agroecological Symbiosis Agric. Syst. 170 39–48

[1] *Lighthouse farms als wereldklaslokaal voor duurzame voedselproductie* – Annemiek Pas Schrijver & Rogier Schulte 68 in de Zwarte, I. J. J., & Candel, J. J. L. (eds.) (2020). *Tien miljard monden: Hoe gaan we de wereld voeden in 2050*. Prometheus.

Santos P Z F, Crouzeilles R and Sansevero J B B (2019). Can agroforestry systems enhance biodiversity and ecosystem service provision in agricultural landscapes? A meta-analysis for the Brazilian Atlantic Forest For. Ecol. Manage. 433 140–5

Valencia V, Bennett E M, Pas Schrijver A, Altieri M A, Nicholls C I, Schulte R P. Under review. Learning from the Future: mainstreaming disruptive solutions for the transition to sustainable food systems. Environmental Research Letters.

Case study 2: Global Yield Gap Atlas – benchmarking opportunities to increase crop production and enhance resource use efficiency

Description

Feeding a growing population within ecological planetary boundaries is one of the grand tasks of humankind in the 21st century and at the heart of multiple Sustainable Development Goals (SDGs). While how this is done will vary across the world, as influenced by each country's phase of economic development, culture, and endowments of climate, soil, and water resources, in all cases effective priority setting for research and development requires accurate data on crop yields and use of natural resources, achieved with both current production methods and improved ones. This insight reveals the scope to enhance production with sustainable use of finite natural resources and limited environmental impact. Effective priority setting also requires sufficient local and global rigour of the data to allow for well-informed and well-targeted interventions in terms of geographical regions, agricultural systems, and ex-ante assessment of potential impact.

To fill this void, the Global Yield Gap Atlas (GYGA) was established in 2011 with the goal of providing public access to accurate estimates of actual and potential yields, yield gaps and the use of land, water and nutrients for all key production areas of major food crops worldwide (Figure 1 and 2). To make this a feasible proposition, GYGA scientists developed a novel "bottom-up" spatial framework to organize soil, climate, and cropping system data, which in turn enabled focus on the key production areas of the most important food crops in each food-producing country. The framework thus minimizes the number of locations from which data are required to obtain robust estimates of yield gaps and required water and nutrient inputs at regional and national scale. Preference for use of primary data and the need for local knowledge of agronomic practices used to produce the major food crops also drives the need for collaboration with leading agronomists in countries that are included in the Atlas

Scientific and societal impact

GYGA (http://yieldgap.org/) now provides a rigorous, publicly available global database that can simultaneously address questions that involve trade-offs among food production, finite resources and environmental impact. GYGA currently covers ca. 70 countries (Figure 3). With GYGA's initial focus on the major cereal crops, it now covers 80-90% of global rice, maize and soybean production, and ca. 60% of wheat. In a number of countries the Atlas also includes a growing number of crops, including sorghum, potato, and grain legumes. GYGA protocols and methods (Van Ittersum et al., 2013; Grassini et al., 2015; Van Bussel et al., 2015) and applications (e.g. Van Ittersum et al., 2016; Rattalino Edreira et al., 2018; Schils et al., 2018) has been published in more than 30 scientific papers (see www.yieldgap.org for full list), many of which are highly-cited. In a recent paper we compared the yield gaps estimated in GYGA (labelled a bottom-up approach) with those estimated in so-called global-gridded simulations (labelled top-down approaches) and showed that the latter lack local rigour and even sometimes miss accuracy at sub-continental level (Rattalino Edreira et al., 2021). In recent years GYGA is also increasingly used by scientists not directly engaged in its development (Van Zeist et al., 2020; Amelung et al., 2021). GYGA databases are widely used by public and private sectors, NGOs and academia, with an average annual ca. 35,000 users of the website and over 4,000 data downloads (average numbers over 2017-2020). It is used for three overall purposes: a. a foundation for detailed on-the-ground studies to understand yield gaps and identify agronomic and policy options for increasing food production while conserving natural resources (e.g. Silva et al., 2017; 2021; Van Dijk et al., 2020); b. ex-ante and ex-post impact assessment of R&D investments and technology use (Andrade et al., 2018); c. quantitative foresight studies on food security and natural resources (Van Ittersum et al., 2016; Van Loon et al., 2019 – Figure 4 and 5). Since 2019 the yield gap closure indicator, directly based on the Global Yield Gap Atlas, has been endorsed by the Sustainable Development Solutions Network (www.sustainabledevelopment.report) as an official SDG2 indicator for agricultural productivity, so far for OECD countries (Figure 6).

Next steps

In summary, the GYGA collaboration has developed a robust methodology for estimating yield gaps at local to global scale and the database as well as the methods and underpinning data are made available to the public for research and education. As such, it is now the world's leading agronomic database on crop yield gaps and natural resource use supported by transparent and detailed protocols and expertise from national experts worldwide. It provides decision makers with robust data to develop pathways in sustainable agricultural development and resource use and conservation. Proposed next steps include:

1. Full coverage of the key food producing countries and key food crops in the world;
2. Extension towards natural resource use, actual and future, incl. water and nutrients;
3. Addition of effects of climate change;
4. Developing and implementing a value creation trajectory to maintain and extend the Atlas.

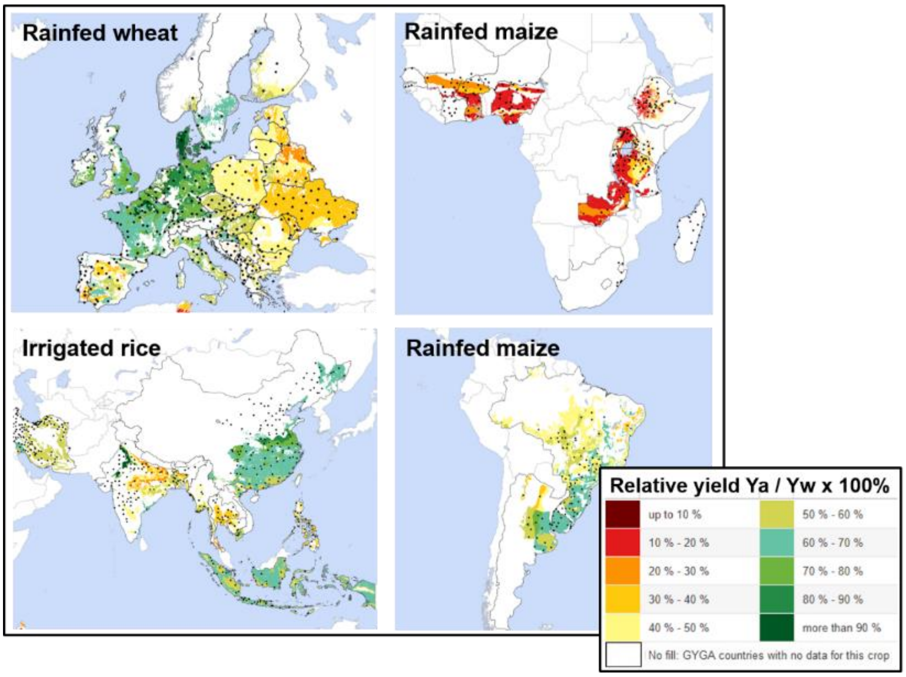


Figure 1. Relative yields (actual farmers' yields as a percentage of potential yields) for a) rainfed wheat in Europe; b) rainfed maize in sub-Saharan Africa; c) irrigated rice in Asia; d) rainfed maize in Latin America. Points are weather stations. Only countries for which the crop is covered in the Global Yield Gap Atlas are shown (https://yieldgap.org/).

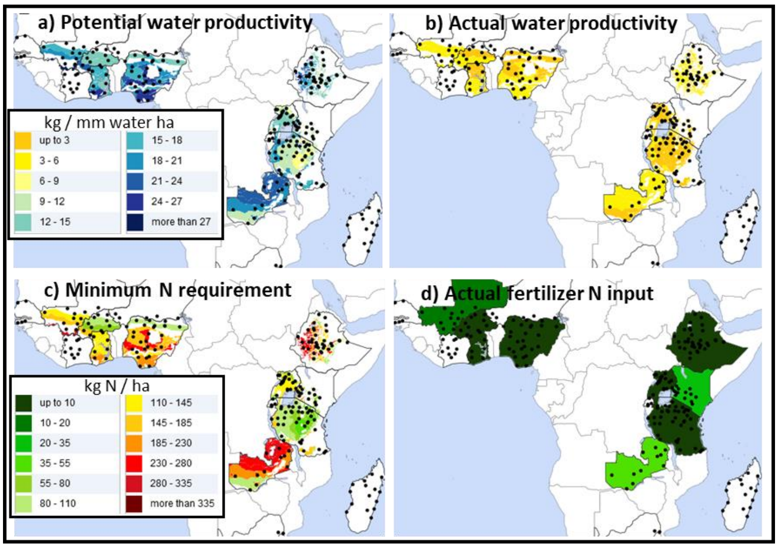


Figure 2. Upper maps: Potential (left) and actual (right) water productivity (both in kg/mm water/ha) in sub-Saharan Africa. Lower graphs: Minimum nitrogen (N) requirements for 80% of the water-limited yield potential of rainfed maize (left) and actual nitrogen fertilizer use (right) in sub-Saharan Africa (both in kg N/ha). Source: http://yieldgap.org/

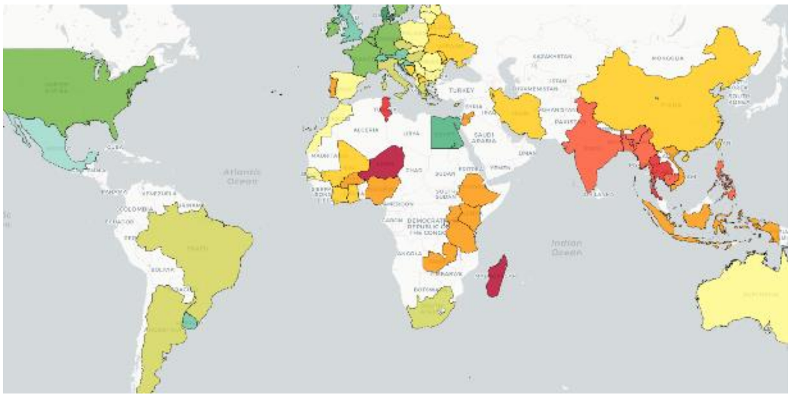


Figure 3. Countries involved in GYGA

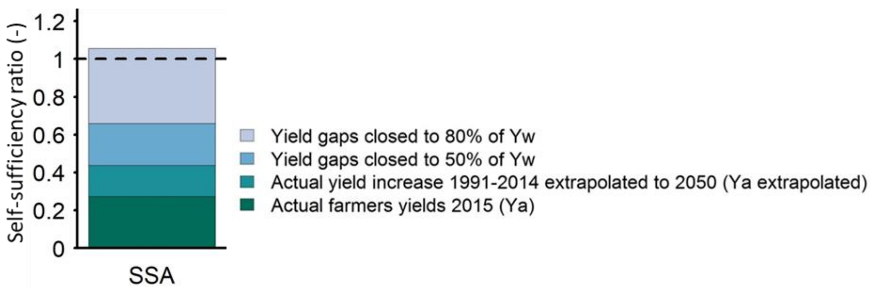


Figure 4. Assessment of cereal self-sufficiency of sub-Saharan Africa in 2050 with different yield increases on existing agricultural land (Update from van Ittersum et al. (2016)). Ratio = 1 means a region is producing enough for its own consumption; Yw = yield potential under rainfed conditions and Ya = actual farmers' yields.

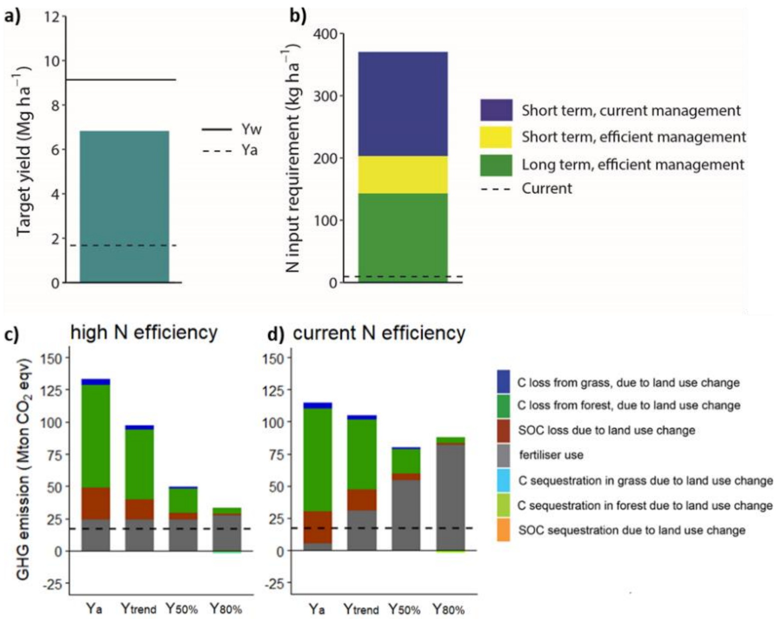


Figure 5. Estimated target yields and nitrogen requirements (kg N/ha) to achieve maize self-sufficiency in 10 countries in sub-Saharan Africa by 2050, and greenhouse gas emissions resulting from alternative scenarios of area expansion (Ya and Ytrend) or intensification (Y50% and Y80%) under high or current N use efficiency (Ten Berge et al. (2019), van Loon et al. (2019)).

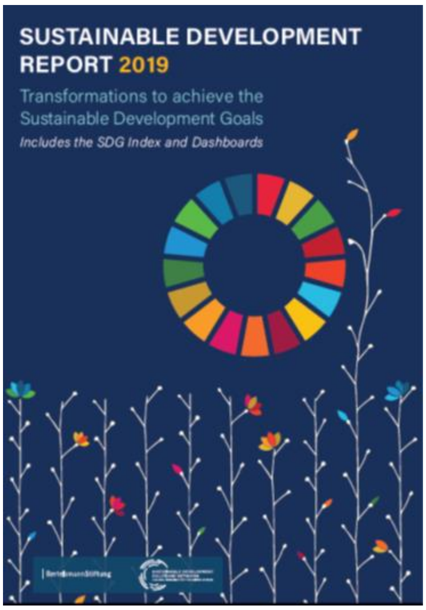


Figure 6. Since 2019 The yield gap closure indicator is used for the assessment of SDG2 by the United Nations Sustainable Development Solutions Network (UN-SDSN)

Selected References:

Andrade, J.F., Rattalino Edreira, J.I., Farrow, A., van Loon, M.P., Craufurd, P.Q., Rurinda, J., Zingore, S., Chamberlin, J., Claessens, L., Adewopo, J., van Ittersum, M.K., Cassman, K.G., Grassini, P., 2019. A spatial framework for ex-ante impact assessment of agricultural technologies. Global Food Security 20, 72-81.
Amelung et al., 2021. Towards a global-scale soil climate mitigation strategy. Nature Communications 11, 5427.
Grassini, P., Lenny G.J. van Bussel, Justin van Wart, Joost Wolf, Lieven Claessens, Haishun Yang, Hendrik Boogaard, Hugo de Groot, Martin K. van Ittersum, Kenneth G. Cassman, 2015. How

good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. Field Crops Research 177: 49-63.

Rattalino Edreira, J.I., Andrade, J.F., Cassman, K.G., Van Ittersum, M.K., Van Loon, M.P., Grassini, P., 2021. Spatial frameworks for robust estimation of yield gaps. Nature Food https://doi.org/10.1038/s43016-021-00365-y

Rattalino Edreira, J.I., Guilpart, N., Sadras, V., Cassman, K.G., van Ittersum, M.K., Schils, R.L.M., Grassini, P., 2018. Water productivity of rainfed maize and wheat: A local to global perspective. Agricultural and Forest Meteorology 259, 364-373.

Schils, R., Olesen, J.E., Kersebaum, K.-C., Rijk, B., Oberforster, M., Kalyada, V., Khitrykau, M., Gobin, A., Kirchev, H., Manolova, V., Manolov, I., Trnka, M., Hlavinka, P., Paluoso, T., Peltonen-Sainio, P., Jauhiainen, L., Lorgeou, J., Marrou, H., Danalatos, N., Archontoulis, S., Fodor, N., Spink, J., Roggero, P.P., Bassu, S., Pulina, A., Seehusen, T., Uhlen, A.K., Żyłowska, K., Nieróbca, A., Kozyra, J., Silva, J.V., Maçãs, B.M., Coutinho, J., Ion, V., Takáč, J., Mínguez, M.I., Eckersten, H., Levy, L., Herrera, J.M., Hiltbrunner, J., Kryvobok, O., Kryvoshein, O., Sylvester-Bradley, R., Kindred, D., Topp, C.F.E., Boogaard, H., de Groot, H., Lesschen, J.P., van Bussel, L., Wolf, J., Zijlstra, M., van Loon, M.P., van Ittersum, M.K., 2018. Cereal yield gaps across Europe. European Journal of Agronomy 101, 109-120.

Silva, J.V., Reidsma, P., Laborte, A.G., van Ittersum, M.K., 2017. Explaining rice yields and yield gaps in Central Luzon, Philippines: An application of stochastic frontier analysis and crop modelling. European Journal of Agronomy 82, 223-241.

Silva, J.V., P. Reidsma, F. Baudron, M. Jaleta, K. Tesfaye, M.K. van Ittersum, 2021. Wheat yield gaps across smallholder farming systems in Ethiopia, Agron. Sustain. Dev., 41 (2021). 10.1007/s13593-020-00654-z

Ten Berge, H.F.M., Hijbeek, R., Van Loon, M.P., Rurinda, J., Tesfaye, K., Zingore, S., Craufurd, P., Van Heerwaarden, J., Brentrup, F., Schröder, J.J., Boogaard, H.L., De Groot, H.L.E., Van Ittersum, M.K., 2019. Maize crop nutrient input requirements for food security in sub-Saharan Africa. Global Food Security 23, 9-21. (FWCI: 7.0)

Van Bussel, L.G., Grassini, P., Van Wart, J., Wolf, J., Claessens, L., Yang, H., Boogaard, H., de Groot, H., Saito, K., Cassman, K.G., Van Ittersum, M.K., 2015. From field to atlas: Upscaling of location-specific yield gap estimates. Field Crops Research 177, 98-108. (FWCI: 6.0)

Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—a review. Field Crops Research 143, 4-17. (FWCI: 32.5)

van Ittersum, M.K., van Bussel, L.G., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., Claessens, L., de Groot, H., Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., van Oort, P.A., van Loon, M.P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, R., Kaizzi, K., Kouressy, M., Makoi, J.H., Ouattara, K., Tesfaye, K., Cassman, K.G., 2016. Can sub-Saharan Africa feed itself? Proceedings of the National Academy of Sciences of the United States of America 113, 14964-14969. (FWCI: 8.5)

van Loon, M.P., Hijbeek, R., Ten Berge, H.F.M., De Sy, V., Ten Broeke, G.A., Solomon, D., van Ittersum, M.K., 2019. Impacts of intensifying or expanding cereal cropping in sub-Saharan Africa on greenhouse gas emissions and food security. Global Change Biology 25, 3720-3730. (FWCI: -)

Van Zeist et al. (2020), Are scenario projections overly optimistic about future yield progress? Global Environmental Change 64, 102120.

For more references: see https://www.yieldgap.org/web/guest/gyga-publications

Case study 3: FOREFRONT Programme- Nature's benefits in agroforest frontiers: linking actor strategies, functional biodiversity and ecosystem services

Description

FOREFRONT is an interdisciplinary, international, comparative research programme that aims to design and negotiate strategies for land use that reconcile the maintenance of biodiversity, the supply of a wide portfolio of ecosystem services (the benefits that humans derive from nature), and meet the needs of local actors who depend on them. The programme focuses on understanding the mechanisms that underlie and drive social-ecological systems, including the complex and shifting institutional arrangements, but also ecological dynamics.

FOREFRONT takes place in Mexico (two research sites) and Brazil (one research site) in order to allow a comparative approach. The landscapes in the three research sites consist of a mosaic of contrasting land uses (Figure 1), and are highly dynamic, reflecting continuous changes in the interactions between people and the environment. In many cases there is a shift towards more agricultural land and this expanding agricultural frontier results in deforestation, however, there are also cases of increased forest cover, known as the forest transition that has been described for various parts of the world. The contested agroforest frontiers found in these landscapes reflect gradients in formal and informal institutional arrangements, governance, regulations and local implementation. This diversity has resulted in a large variation of interactions between people and their environment, culturally and historically defined, and shaped by geo-political and geo-biophysical boundary conditions.

Landscapes are therefore complex social-ecological systems, and their study demands interdisciplinary collaboration between natural and social scientists as well as the integration of different spatial-temporal levels.

The programme has three main objectives:

1. To identify and understand the ecological and social drivers that shape agroforest frontier landscapes and their ecosystem services;
2. To explain temporal changes in the social-ecological system and their consequences for landscape configurations;
3. To design adaptive strategies to balance and optimise the supply of ecosystem services in changing landscapes.

Funding and partnership

FOREFRONT is primarily funded by INREF, the International Research and Education Fund of Wageningen University. As an interdisciplinary programme it transcends the limits of graduate schools and, next to the Graduate School PE&RC, also the Wageningen School for the Social Sciences (WASS) has been involved. Next to funding by Wageningen University (m€ 1.2), also funding by the other partners, in cash or in kind (to a total value of m€ 1.1) is mandatory. The collaborating institutes (Mexico: Instituto de Investigaciones en Ecosistemas y Sustentabilidad, UNAM, Morelia; Mexico: El Colegio de la Frontera Sur, San Cristóbal de las Casas; Brazil: Federal University of Viçosa, Brazil) also provided support through the appointment of additional PhD candidates and post-docs, staff time, research facilities, etc. All three institutes had long-standing collaboration with chair groups of Wageningen University. At each research site there has been long-standing collaboration between academia and local partners (NGOs, farmer unions, etc.). Financial support was also provided by Tropenbos International, because of joint interest in understanding and managing this dynamic forest frontier.

Figure 1. The frontier between agricultural land and forest

Scientific impact

Education of a new academic interdisciplinary generation
The programme will educate 11 PhD candidates, of which 8 will graduate at Wageningen University, three of which being double degrees together with the Federal University of Viçosa. Next to interdisciplinary research, the programme contributes to (further) incorporation of interdisciplinarity in academic institutions, both in Wageningen and in the partner institutes.

Ecosystem services
In all three sites the ecosystem services provided by soils and the aboveground vegetation types (forest, agroforests, croplands, rangelands) have been inventoried and quantified (Teixeira, 2020; Gomes, 2020; Aguilar-Fernández et al., 2020; Hernández Guzmán, 2021). Special attention was devoted to the links between biodiversity and ecosystem services as well as conditions under which provisioning services (agricultural production and production of forest materials) are traded-off against or show synergy with the other categories of ecosystem services (supporting and regulating services, cultural services). Limits to the usefulness of the concept of ecosystem services as traditionally understood (the benefits that humans derive from ecosystems) emerged from such analyses, and a more encompassing framework that looks at human co-production of those services (Heinze et al., 2021a) was considered a better way for both analytical purposes and for designing strategies for land uses that could combine productive activities with nature conservation. Further elaboration of this concept of co-production in relation to agroecological design remains a challenge for the future. Future research is also needed on spatial upscaling of ecoservices. Currently services are assessed per ecosystem, but provision of these services depends on the landscape configuration. In the framework of the debate on land sparing versus land sharing, this landscape configuration demands further attention.

Understanding the forest transition
Based on a newly developed method Lohbeck et al. (2021) analysed and quantified land use changes in Marques de Comillas over the last thirty years. The region exhibited more forest losses and gains, resulting in a net decrease of 30% forest cover, however there were several signs indicating that farmers gradually move away from swidden agriculture towards more permanent use of agricultural land, which would further forest recovery. Especially in areas with higher soil quality there are further possibilities for forest recovery through more permanent land use. However, competition for forest conservation and agricultural land use will likely persist in the future, necessitating institutional support and incentives for sustainable land use. The same method will now by applied in a comparative approach in the three research sites to understand

generalities in this model of forest transition and to help advancing ways to combine sustainable agriculture and nature conservation.

Scenario studies
One of the aims for FOREFRONT is to design adaptive strategies. The programme achieved that goal by pursuing scenario studies. Gomes et al. (2020) conducted a spatially explicit analysis to assess the area in Zona da Mata that, under the likely scenario of global climate change, would be suitable for coffee production in 2050. The data show that climate change will reduce conventional coffee production (sun coffee) in the current area with around 60%. However, agroforestry practices with shade coffee will to a substantial degree mitigate this negative effect. Climate change will result in shifts in areas that are suitable for coffee and hence is a potential driver for future conflicts between nature conservation and coffee production. Heinze et al. (201b) assessed ecosystem services in La Sepultura under alternative land use scenarios, focusing on ecosystem services trade-offs at the farm and landscape level. Farm diversity critically mattered, as the magnitude of these trade-offs varied considerably among small vs. large farms. Some scenarios presented hard trade-offs, compared to the more moderate integrated agroforestry practices scenario. The land use zoning scenario, a management strategy promoted by conservation institutions, did not differ from the current landscape nor offer an improvement in conservation indicators.

Social-science research
In Marques de Comillas, Berget et al. (2021) analysed the histories of two communities (*ejidos*) who colonised the area only a few decades ago and thereby created the forest frontier in an area that had known very little human impact in the past centuries. The PhD thesis by Goris (2020) dealt with the engagement of Brazilian youth in agroecological farming in the Zona da Mata, Brazil. The research departed from mainstream approaches that often focused on understanding causes why young people migrate out of rural areas and therefore move out of agriculture. The research by Goris focused on the space (physical and social) that young people create towards agroecological practices that result in ecologically and socially sustainable food systems. Together with the PhD thesis by Van den Berg (2020), the programme contributed to understanding and advancing agroecological movements in Brazil. Cruz-Morales (2021) studied attitudes and knowledge of children and teenagers towards the forest frontier in the MAB reserve La Sepultura, Mexico.

Societal impact

FOREFRONT invested in stakeholder collaboration and sought collaboration with local farmers and farming communities, but also institutions in the domain of nature conservation. In the closing workshop in Viçosa (March 2020, just before the covid-19 pandemic brought the world close to a standstill, there was ample space to interact with these farming communities. FOREFRONT organised several local workshops, field visits together with involved farmers, participated in social activities, produced and promoted booklets and videos, sought media-exposure. During the closing workshop a video was made. The main purpose of the video is to show the importance of collaboration (between universities in the global north and south; between natural and social science in an interdisciplinary context; and between science and local knowledge as embodied in the practices of agroecological farmers) to generate knowledge relevant for the sustainable-development goals (SDGs) and that supports educating a new generation of interdisciplinary academics (FOREFRONT YouTube channel). In the research site of Marques de Comillas, Mexico, FOREFRONT collaborated with an NGO called Cascoland to set up a Lab & Kitchen project (Cocina Colaboratorio) to help people recognise, appreciate and use local (forest) plants with a high value for food and other uses, while simultaneously contributing to biodiversity conservation. These activities fit in a larger global movement towards food forests.

Next steps

The FOREFRONT programme will formally close on December 31st, 2021. During the final workshop in Viçosa a number of concluding activities were identified and planned (Figure 2).

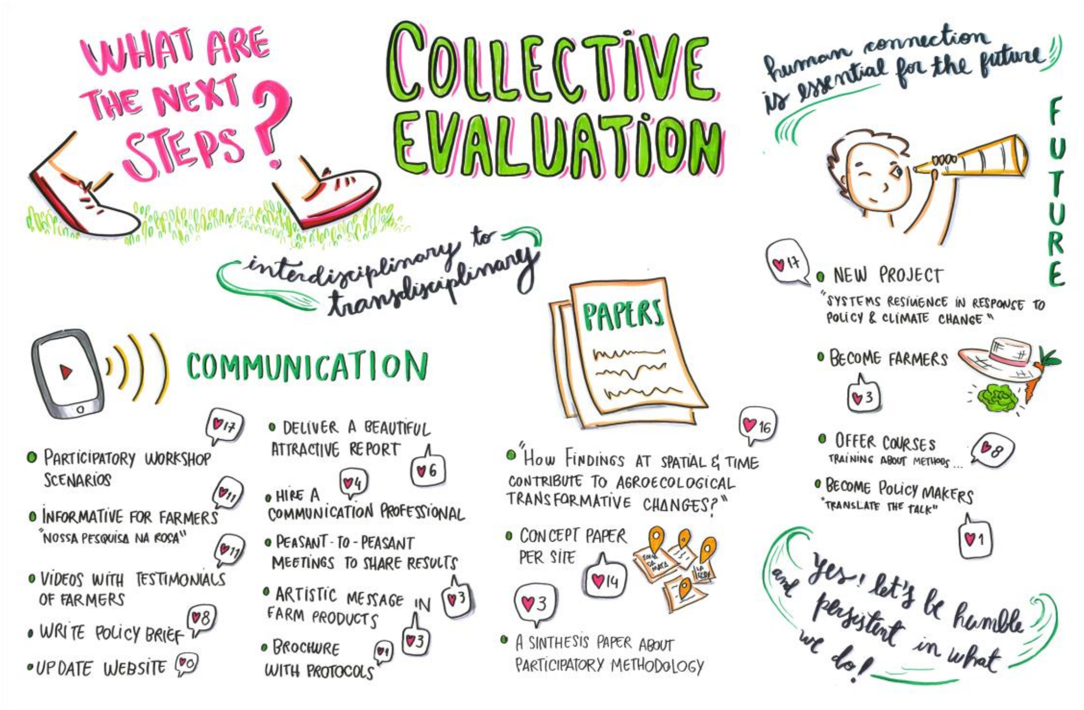


Figure 2. Concluding activities of the FOREFRONT programme.

Currently five post-doctoral researchers have been (part-time) appointed to:

- Further analyse histories of deforestation and reforestation in the framework of general theories on the forest transition;
- To provide a general reflection on the usefulness of the concept of ecosystem services, considering the social co-production of these services.
- To integrate the results per research sites
- To further develop communication strategies towards local stakeholders

References

Aguilar-Fernández, R., M.E. Gavito, M. Peña Claros, M. Pulleman & T.W. Kuyper (2020). Exploring linkages between supporting, regulating, and provisioning ecosystem services in rangelands in a tropical agro-forest frontier. Land 9: art. 511.

Berget, C., M. Lohbeck, G. Verschoor, E. Garcia Frappoli & F. Bongers (2021) Smallholder land-use decisions in a tropical agro-forest frontier: The comparative case of two communities in Southern Mexico. Under review.

Cruz-Morales, J. (2021). Construyendo juntos una montaña feliz. In press.

Gomes, L.C. (2020. Land use change and ecosystem services: linking social and ecological systems across time. PhD thesis, Wageningen University & Federal University of Viçosa; 217 p.

Gomes, L.C., F.J.J.A. Bianchi, I.M. Cardoso, R.B.A. Fernandes, E.I.F. Filho & R.P.O. Schulte (2020). Agroforestry systems can mitigate the impacts of climate change on coffee production: a spatially explicit assessment in Brazil. Agric., Ecosyst. Environ. 294: article 106858.

Goris, M. (2020). Emancipation of young agroecological peasants in Zona da Mata, Minas Gerais, Brazil: an identity-in-the-making. PhD thesis, Wageningen University & Federal University of Viçosa; 200 p.

Heinze, A., F. Bongers, N. Ramírez Marcial, L.E. García Barrios & T.W. Kuyper (2021b). Scaling up land use scenarios from farm to landscape level through ecosystem services assessment. Under review.

Heinze, A., T.W. Kuyper, L. García Barrios, N. Ramírez Marcial & F. Bongers (2021a). Tapping into nature's benefits: values, effort and the struggle to co-produce pine resin. Ecosyst. People 17: 69-86.

Hernández Guzmán, A. (2021). Ecosystem services provided by soils in a Mexican agro-forest landscape. PhD thesis, Wageningen University; 154 pp.

Lohbeck, M., B. DeVries, F. Bongers, M. Martinez-Ramos, A. Navarrete-Segueda, S. Nicasio-Arzeta, C. Siebe, A. Pingarroni, G. Wiess & M. Decuyper (2021). Mexican agricultural frontier communities differ in forest dynamics with consequences for conservation and restoration. Revision submitted.

Teixeira, H.M. (2020). Linking biodiversity, ecosystem services and social actors to promote agroecological transitions. PhD thesis, Wageningen University & Federal University of Viçosa; 287 p.

Van den Berg, L. (2020). Building movements for the transformation: defending and advancing agroecology in Brazil. PhD thesis, Wageningen University; 124 pp.

Case study 4: Re-designing photosynthesis for future cropping systems

Description

Photosynthesis is a fundamental process that is the basis of life on planet earth. During photosynthesis light energy is captured and converted into chemical energy which is then used to fix carbon dioxide. At the same time it is a process that reflects the current performance of a crop and its sensitivity to stress, such as cold, heat, drought, fluctuating light, and nutrient shortage, because photosynthesis has a short response time to stress. Photosynthesis is also an important frontier for crop improvement, especially under climate change (Figure 1).

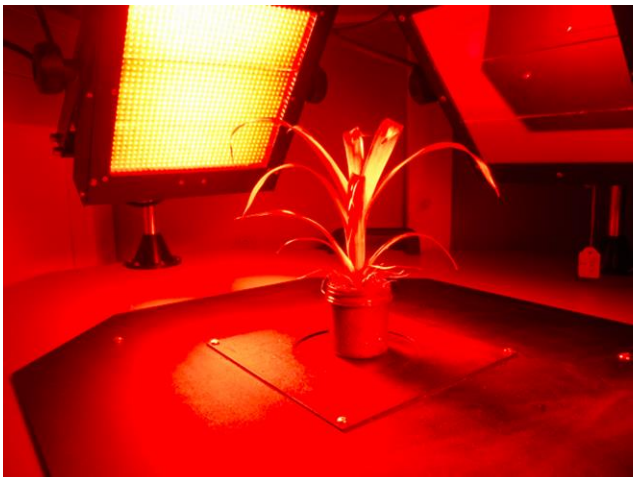


Figure 1. Photosynthesis is an important frontier for crop improvement

Within PE&RC photosynthesis is being investigated at various scales of time (from picoseconds to growing season), organization (from the molecular level to the crop level) and with many different objectives (using genetic variation, designing ideotypes, creating more robust plants, creating more efficient canopies, optimizing light profiles, increasing energy efficiency in crop production). Although the biophysical aspects of the primary photon capture is mainly the domain of Experimental Plant Sciences, there is significant interaction between Biophysics and research groups within PE&RC. The same applies to the Biochemistry aspects. Within PE&RC photosynthesis is investigated by many chair groups, for example by Horticulture & Product Physiology, Crop Physiology, Crop and Weed Ecology, Forest Ecology, Plant Production Systems, and other groups, in different production systems: from vertical farms and greenhouses to annual and perennial crops, to polycultures and intercropping systems, forests, grassland vegetations etc. Within PE&RC the focus lies at processes at sub-leaf level, leaf level, plant level and canopy level, although the research on modelling can encompass a much wider range of organization levels.

Important large-scale projects are for example the "Extremophiles project", "Led it be: smart LED lighting" and "SKY HIGH: Urban farming and vertical farming". In the Extremophile project photosynthetic super-performers that are closely related to crop species are analysed for their photosynthetic machinery and the underlying genetic differences and variation. In this programme PE&RC is mainly involved in the modelling of the light propagation and gas exchange inside the leaf as affected by micro-anatomy (Figure 2). For that purpose, reaction-diffusion models are coupled to light penetration models, the three-dimensional geometry of leaves and the three-dimension distribution of carboxylation capacity. With this programme we will develop new avenues to improve the efficiency of photosynthesis.

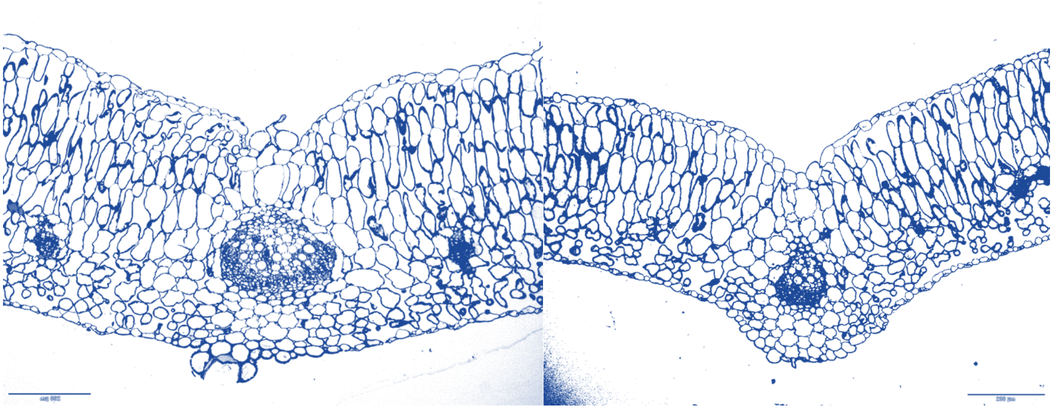


Figure 2. Anatomy of super-performer Hirschfeldia incana under high (left and low (right) light

The "Led it be" programme has been developed to save energy for lighting. Switching from high pressure sodium lamps (HPS) to LED-lighting already results in a 25% saving on energy consumed in a greenhouse. An additional 30% reduction in electricity use might be achieved by smart positioning of LEDs and new light recipes maximizing plant light use efficiency by adjusting light intensity and quality through time (Figure 3). Because LED lights do not produce heat, they can be placed between plants and provide light from different directions (e.g. side and bottom) compared with traditional top lighting. This enables to provide a more homogeneous distribution of the light within the canopy whilst keeping the total intensity constant. As a result, the plant can achieve a higher light use efficiency and yield at a similar lighting cost.

Experimental and modelling research on photosynthesis also focuses on the opportunities for acclimation of photosynthesis to fluctuating light, different light levels, temperature, drought and carbon dioxide concentration in the ambient air. Modelling research focuses on energy budgets of the various subtypes of C4 photosynthesis and on the C2 and C3/C4 intermediate types.

Figure 3. Interlighting in a greenhouse crop stand

In the project "SKY HIGH: Urban farming and vertical farming", we develop concepts for design and control of vertical farms. This can secure a sustainable vegetable supply in urban areas. These vegetables have a greatly improved quality (taste, aroma, appearance, shelf life, nutritional value, safety) every day of the year independent of weather compared with conventionally produced (greenhouse grown or field-grown) vegetables. Maximizing productivity in vertical farm is achieved by an optimized lighting control (quality and quantity) maximizing photosynthesis through time and reducing energy use (Figure 4).

Figure 4. Vertical farming

Scientific and societal impact

Photosynthesis research at Wageningen University and Research has profited greatly from the nation-wide research programme Towards BioSolar Cells, which run from 2011 – 2016. In this programme many PhD candidates were trained and became experts in the field of photosynthesis. Moreover, the programme resulted in many new nation-wide linkages. In the aftermath of the programme many new international, national and local initiatives were created. Funding resources came from the National Science Foundation and private donors, whereas in the near future large EU research programmes focusing on photosynthesis will be initiated. It resulted in a continuous stream from Wageningen of high-quality research papers (according to Scopus, about 170 per year for the last 6 years) and Wageningen presentation in (the organization of) international scientific conferences on photosynthesis, such as the 17th International Conference on Photosynthesis Research in Maastricht in 2016. Moreover, Wageningen educated staff spread around the world to work in top photosynthesis research laboratories before returning to Wageningen, strengthening the international ties and taking a lot of experience with them. This impact on the research agenda of Wageningen University and Research and the quality of the research staff will be long lasting. PE&RC can play a strong part in capitalizing on that wonderful human resource.

Not only research but also education has profited significantly from this strong interest in photosynthesis. New courses have been developed, new educational tools have been created, especially relating to the quantitative analysis of photosynthesis, and several PE&RC courses on photosynthesis with both local, national and international speakers and participants have taken place.

These developments are all very necessary. Photosynthesis will play a key role in realizing food security in the future. In order to realize the required production of arable and horticultural farming to feed the growing population with its changing demand it is necessary to improve the efficiency of photosynthesis in a coherent way. We will need to redesign photosynthesis in order to make sure that crops can make maximum use of the resources offered to them by growers. This will not only make the production more efficient, but also more sustainable. It is also necessary to link photosynthesis to other processes and phenomena, such as the distribution of nutrients within the plant stand, the sink-source relationships, stress tolerance, etc., as photosynthesis will determine potential yield but not always actual yield. Photosynthesis research will enhance the development of new, innovative production systems, such as vertical farms, plant production systems in space stations, and intercropping systems. It will help create better food systems, help to play a role in creating a circular agriculture with a much stronger focus on local production and a keen eye on the carbon, nitrogen and water cycles. Moreover, photosynthesis research will be vital for a biobased economy. PE&RC is very well positioned to realize such research in a well-structured, coherent and societally relevant way.

Next steps

Climate change affects photosynthesis in different ways. Scarcer water and nutrients due to changes in precipitation patterns and soil erosion affects the photosynthetic capacity of the plant. Higher atmospheric [CO_2] allows plants to use less water and photosynthesize more (especially for C_3 plants). However, warmer temperatures make plants use more water and photosynthesize less. Therefore, plants will have to acclimate to new conditions in a near future, which will impact species distribution and crop yield (Figure 5). Genetic controls of photosynthesis were shaped by the native environments of the crop ancestors, which may not be optimal for current agro-ecosystems and future environmental conditions. Under a dynamic environment, plant photosynthesis can be inefficient due to the limited CO_2 diffusion from the outsides leaf to the sites of CO_2 fixation and the need to activate enzymes such as Rubisco (ribulose-1,5-bisphosphate carboxylase/oxygenase). Reducing these photosynthesis limitations to increase or maintain crop yield under conditions matching future climate is important for food security and production of biobased raw materials.

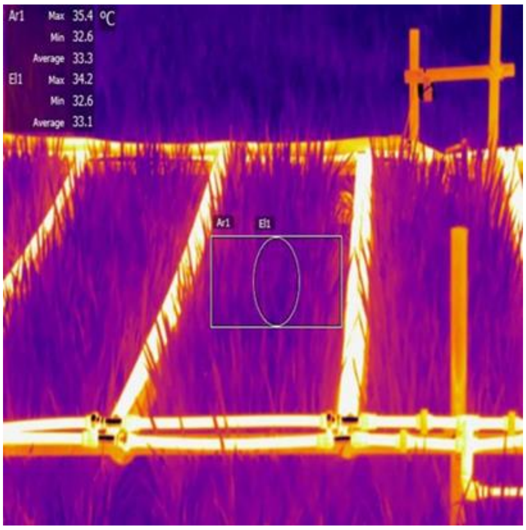


Figure 5. Canopy temperatures in a T-FACE set-up to study the effects of enhanced CO_2 concentration and elevated temperature in the field.

The intensity of solar light in greenhouses often fluctuates rapidly and strongly, to which photosynthesis processes are not always prepared resulting in inefficient light use. This is a strongly complicating factor in field conditions. Almost all models of photosynthesis are steady-state models. Recently PE&RC staff has worked on photosynthesis under fluctuating light and has demonstrated that there are large inter- and intra-species differences in efficiency of coping with fluctuating light. C_4 species are notoriously poor in coping with such conditions. A new project aims to dynamically control LED lighting by coupling a mechanistic model of dynamic photosynthesis and a sensor to monitor photosynthetic induction state. Using this approach, annual electricity used for lighting could be reduced by 10% without losses in production, compared to constant lighting.

Based on the ongoing prospects we will continue to explore opportunities to re-design photosynthesis and apply possible avenues for improvement to crop plants. This will entail both classical approaches on the basis of existing natural variation as well as approaches based on genetic modification or mutants. The approaches within PE&RC go beyond most ongoing research programmes because of the instruments and tools to scale up from molecular level to crop level and from the lab into farmers' fields.

Recent publications

Morales, Alejandro, Elias Kaiser, Xinyou Yin, Jeremy Harbinson, Jaap Molenaar, Steven M. Driever & Paul C. Struik, 2018. Dynamic modelling of limitations on improving leaf CO2 assimilation under fluctuating irradiance. Plant, Cell & Environment 41(3): 589-604.

Yin, Xinyou & Paul C. Struik, 2018. The energy budget in C4 photosynthesis: insights from a cell-type specific electron transport model. New Phytologist 218:986-998.

Earles, J. Mason, Thomas N. Buckley, Craig R. Brodersen, Florian A. Busch, F. Javier Cano, Brendan Choat, John R. Evans, Graham D. Farquhar, Richard Harwood, Minh Huynh, Grace P. John, Megan L. Miller, Fulton E. Rockwell, Lawren Sack, Christine Scoffoni, Paul C. Struik, Alex Wu, Xinyou Yin, Margaret M. Barbour, 2019. Embracing 3D complexity in leaf carbon-water exchange. Trends in Plant Science 24:15-24.

Yin, Xinyou, Ad H.C.M. Schapendonk & Paul C. Struik, 2019. Exploring the optimum nitrogen partitioning to predict the acclimation of C3 leaf photosynthesis to varying growth conditions. Journal of Experimental Botany 70 (9): 2435-2447.

Cai, Chuang, Gang Li, Lijun Di, Yunjie Ding, Lin Fu, Xuanhe Guo, Paul C. Struik, Genxing Pan, Weiping Chen, Weihong Luo & Xinyou Yin, 2020. The acclimation of leaf photosynthesis of wheat and rice to seasonal changes in T-FACE environments. Global Change Biology 26: 539-556.

Zhang, N., Arian van Westreenen, Niels P R Anten, Jochem B Evers, Leo F M Marcelis, 2020. Disentangling the effects of photosynthetically active radiation and red to far-red ratio on plant photosynthesis under canopy shading: a simulation study using a functional–structural plant model, Annals of Botany 126(4): 635–646, https://doi.org/10.1093/aob/mcz197

Yin, Xinyou, Florian A. Busch, Paul C. Struik & Thomas D. Sharkey, 2021. Evolution of a biochemical model of steady state photosynthesis. Invited Review. Plant, Cell & Environment. https://doi.org/10.1111/pce.14070

Zhang, N., Van Westreenen, A., He, L., Evers, J.B., Anten, N.P. and Marcelis, L.F., 2021. Light from below matters: Quantifying the consequences of responses to far-red light reflected upwards for plant performance in heterogeneous canopies. Plant, Cell & Environment, 44(1), pp.102-113.

Research Theme

Ecology, biodiversity & conservation

3. Theme Ecology, biodiversity & conservation

3.1 Summary theme Ecology, biodiversity & conservation

Ecology is at the core of the major scientific task to understand and mitigate effects of global change on our natural environment. We contribute to this task. We share a strong fascination for ecology, a concern about the loss of biodiversity and an associated urgent drive to reverse the current trend of biodiversity decline. The mission of the research theme is to **generate insights into ecological processes and interactions, and use these to inform and design effective strategies for the protection, restoration and sustainable management and use of ecosystems and biodiversity**. We do this by delivering fundamental and applied ecological knowledge, at scales ranging from genes to ecosystems.

We mainly work on three main research lines: (1) deciphering the mechanisms supporting biodiversity and driving ecosystem functioning, (2) quantifying changes in biodiversity and ecosystem functioning and (3) evaluating effectiveness of conservation and management measures. Within these research lines, we combine empirical studies that make use of observational and experimental data, with modelling approaches.

Our societal impact includes the development of transformative pathways leading to societies that can sustainably coexist with nature. We create the tools to support ecological restoration and sustainable resource use. Our societal impact is large at national and international levels: on biodiversity conservation on agricultural lands, nature-friendly and climate-smart forest management, wildlife conservation and rewilding. Our research frequently receives media attention, and we are often requested to comment on news and societal developments.

The coming years, we will focus specific attention to three urgent challenges: (1) **Biodiversity conservation in future landscapes.** The increasing global demand for food and wood takes an ever larger toll on ecosystems, their biodiversity and complex relationships among species worldwide. The challenge is to understand how biodiversity can be sustainably managed in the landscapes at long time scales and under global change. (2). **Providing ecological evidence for ecosystem restoration.** Unprecedented upscaling of restoration efforts is foreseen in the next years. Ecological input is required to deliver the best practices for effective restoration in all biomes, for trees, plants, and wildlife. (3). **Ecosystem resilience to climate extremes.** Climate extremes strongly affect ecosystems and are predicted to intensify. Mitigating the biodiversity implications is a major societal challenge, for which scientific input is needed.

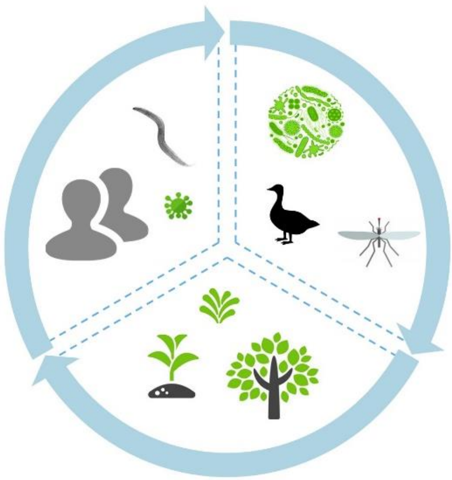
We aim to strengthen our position by increasing the integration within the research theme and by making use of our central position in the recently established Wageningen Biodiversity Initiative (WBI) and the WUR-ESG theme 'Biodiverse environments'. To develop interdisciplinary collaborations, we suggest the PE&RC graduate school to stimulate collaboration within and across research themes by offering funding for integrative research projects. We will discuss options to appoint PhD, post-docs and tenure track researchers that are shared across chair groups within the graduate school and Wageningen University. These actions will allow our research theme to thrive and allow it to provide science-based solutions that will lead to the effective protection, restoration, sustainable use and service provision of ecosystems and the biodiversity they harbour.

3.2 Case Studies theme Ecology, biodiversity & conservation

Three case studies of past and ongoing research. Picture borders reflect the main research lines, see colour coding in Figure 2. **A.** Biodiversity enhances ecosystem functioning, but whether this relation also exists for half of the planet's plant biomass located below ground, is unknown. Combining ecological, molecular biological and epidemiological approaches, we discovered that this relation also holds below-ground. Yet, the mechanism is different and unique: soil microbes and fungal pathogens play a major role. **B.** Criminal networks threaten biodiversity in tropical savannas. To develop an effective anti-poaching system, we analysed behaviour, movement and disturbance responses of antelope species using high-tech movement sensors. Applying AI technology, we built a sentinel-based early warning system that detects human intruders prior to staged poaching events. This successful proof of principle allows upscaling and application in other ecosystems. **C.** High nitrogen deposition poses an important threat to forests located close to high-input agriculture, causing tree mortality and shifting species composition. A possible mitigation measure is the application of rock dust, a slow-release mineral fertilizer. Dutch forest managers consider applying this method, but its effectiveness is unknown. We combine approaches from soil, forest and animal ecology to evaluate effects of rock dust application on forest regeneration and herbivory in large-scale field experiments to provide decision support for forest managers.

Research Theme

One Health



4. Theme One health

4.1 Summary theme One health

One Health is an approach that recognises that human health is closely connected to plant, animal and ecosystem health. The research theme One Health at WUR is organized around experts which belong to four core chair groups (Entomology, Genetics, Nematology, Virology), two additional contributing chair groups (Wildlife Ecology and Conservation, and Crop System Analysis) and individual researchers that are part of PE&RC. The members of the One Health research theme use their "disciplinary" knowledge and expertise to contribute to the theme as a whole and collaborate through specific One Health related research projects in partnership with other WUR groups and institutions in the Netherlands, the EU, and beyond.

*The **mission** of the research theme One Health at Wageningen University & Research (WUR) is to understand ecological, evolutionary, and molecular processes to improve the health of organisms and the environment they live in.* Efforts across human societies have greatly increased living standards and conditions for humans while crucially intensifying agriculture across the globe. However, intensification of agriculture along with the increase in global human population and urbanization has increased the health risks for humans, animals and plants, by increasing the emergence and spread of pests, pathogens and parasites. Climate change may give rise to metabolic disruptions and oxidative stress of individuals and decrease their resistance to different diseases. Furthermore, society experiences everyday consequences of global trade, monocultures, landscape fragmentation, biodiversity loss, non-selective pesticide use and rise in resistance to control measures (e.g. antimicrobial resistance), which all can have health consequences. Looking for the solutions for these societal challenges is the focus of many research projects at the One Health theme at WUR. *The **uniqueness** of the One Health theme at WUR is in the embedding of health while embracing natural and agricultural ecosystem settings, directly linking human health with the health of the environment.*

Collaboration and communication between experts from different fields in a holistic approach are key features of the One Health philosophy. The research theme One Health at PE&RC represents a joint effort, made possible by the exchange of ideas, people, facilities and data, via collaborations between researchers participating in PE&RC. Many of the research projects considered in this document have strengthened their focus and increased their impact through the collaborative effort between different chair groups. The members of the PE&RC contribute to the development of core ideas of health of living organisms and systems by using their state-of-the-art expertise in molecular biology, genetics, evolution, ecology and agriculture. They explore and investigate urgent problems, to find answers to related questions, and/or describe and analyse possible scenarios for solutions to contribute to promotion of health. By working locally, regionally, nationally, and globally, the aim is to retain and recover health for humans, animals, plants, and the environment at these different scales.

With our mix of applied and fundamental research, the output of the research theme helps to solve concrete problems in promoting health and disease control. We aim to link our research, at all stages from initiation to dissemination, to stakeholders to maximize societal impact. In this way we aim to actively connect fundamental science to societal relevance through (applied) research. Stakeholders are manifold. They range from small-holder farmers and consumers in low-resource countries to for-profit companies working in crop protection, animal and human health and disease management, NGOs and (inter)national policy makers in disease control and pest management, and academic and general public.

One Health research theme at WUR is evolving in the direction of taking a more broad perspective of the initial definition of the One Health approach. Even though we extensively work on the original research questions of the One Health like zoonotic diseases, anti-microbial resistance and food safety and security, we are also committed to subjects like nutrition and food quality as well as soil health. These are topics that also receive attention from the One Health perspective. Furthermore, the members of the One Health research theme see a strong incentive to develop cross-disciplinary collaboration with experts from social sciences. The ambition of our members is to increase their visibility in the international circles of One Health research agenda and get recognized for its broad perspective on One Health approach

4.2 Case Studies theme One health

Case Study I - Unravelling the emergence of tick-borne encephalitis in The Netherlands

Tick-borne encephalitis (TBE) is one of the most important arboviral infections in Europe, with 2,000 – 3,500 human cases each year. New endemic foci continue to emerge, both in countries where the virus has been present for a long time (e.g. Finland, France) and those where it was considered to be absent (e.g. the Netherlands, Belgium). With the recent expansion of TBE into the Netherlands and other previously naïve areas, the current distribution of the virus lies beyond what was predicted by past models. The causes of this unexpected spread remain unclear, and public health institutes need better models to identify areas of potential emergence. This underlines the need for systematic data collection across disciplines, such as vector biology, wildlife ecology, virology and public health. Within such a One Health approach, the aim is to unravel local transmission dynamics as a prerequisite for adequate risk management and vaccination programs.

The first evidence of TBEV circulation in the Netherlands was found in 2016. That year, serum samples from 297 roe deer (*Capreolus capreolus*) obtained in 2010 were found positive for the presence of TBEV-neutralizing antibodies. This prompted a survey of *Ixodes ricinus* ticks from the area with positive roe deer, and two ticks were found to carry a unique strain of the European subtype of the virus, confirming the presence of TBEV in the Netherlands. Shortly after communicating these findings to health professionals, the first two autochthonous cases in humans were confirmed in June and July 2016, followed by 1-5 cases each year since then. Interestingly, the strain isolated from one of the patients was different from that detected in ticks, suggesting that multiple TBEV strains circulate in the Netherlands.

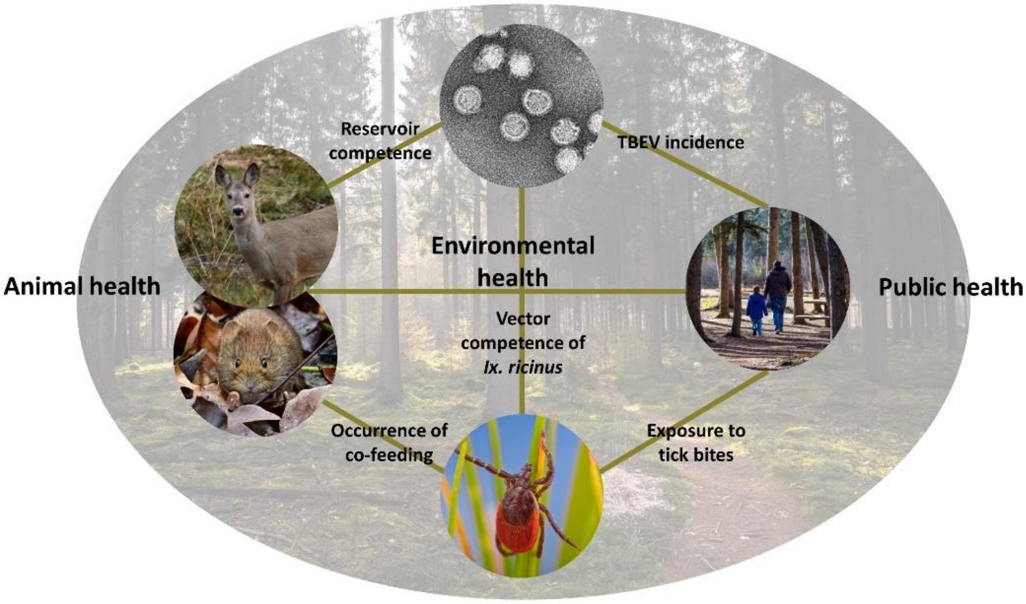


Figure: A One Health approach of tick-borne encephalitis virus by integrating studies on vector biology, wildlife ecology, virology and public health

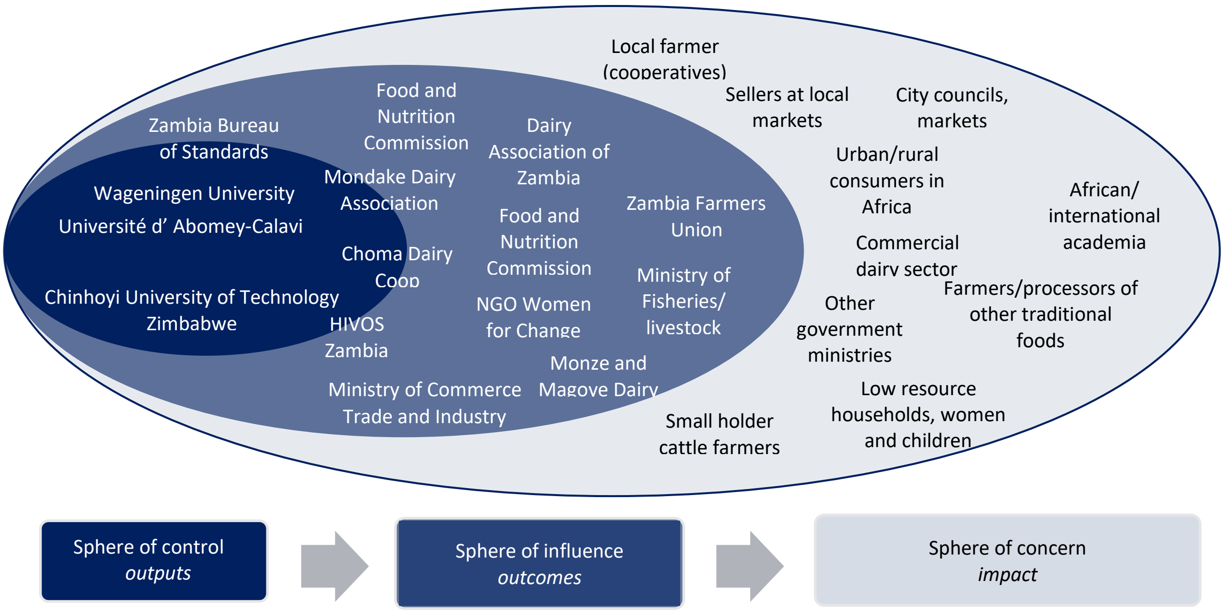
Very little is known about the ecology and epidemiology of TBEV in the Netherlands, or the risk of further expansion of the virus. Over the past years, we have investigated ticks and rodents in the newly identified foci to confirm local circulation of TBEV. Based on these and previous findings, we aim to create risk maps and risk models for the Netherlands. The maps will provide the basis for continued monitoring of known foci and targeted surveillance in potential new sites of emergence. However, the ecological mechanisms that drive local TBEV transmission in these new areas remain unclear. Within our research, we therefore employ an integrated approach of ecological field data collection, laboratory experiments (host-tick transmission experiments), and mathematical modelling to unravel what tick-, host-, and virus-related factors explain the recent emergence of TBEV and which environmental conditions may promote further expansion of the virus in the

Since 2017, the open questions of this new research field have been addressed within a series of projects that have been supported by various funders, including the PE&RC graduate school, NWO-IdeaGenerator, NWO-ZonMw and Pfizer. This has created opportunities for PhD and post-doc researchers to develop their academic careers. Besides the WUR groups of Entomology, Wildlife Ecology & Conservation and Wageningen Bioveterinary Research, project partners include the RIVM and Artemis One Health. In addition, land-owner organizations, such as Staatsbosbeheer and Natuurmonumenten, are important stakeholders for implementation of the research, as well as for communication of the research findings.

Case Study II - Traditional fermented foods to prevent disease, promote general health and livelihoods in Zambia

Fermentation is a process of transformation of raw materials by microbes to produce safe and nutritious foods. Ever since human civilization, this process has been used to preserve raw materials, prevent soilage by pathogens and to promote general health. In this project, we work on traditional fermented foods in Africa. Many of these rely on uncontrolled fermentation of a complex community of microbes. From a fundamental science point of view, these products present an interesting model system to address basic questions on what ecological and evolutionary forces shape (microbial) eco-systems. These studies have many practical and applied implications. The ecology of fermenting microbes ensures the formation of metabolic networks between the lactic acid bacteria responsible for fermentation, thereby allowing other microbes such as pathogens to thrive. Upon human consumption, the complex community of fermenting microbes interacts with the gut microbiota. Our work shows that this interaction between shifts the ecology towards a more favourable composition to inhibit pathogens and to promote a healthy gut environment.

Traditional fermented foods not only are an interesting model system for One Health related questions on inhibition of pathogenic bacteria and promotion of a healthy gut microbiota through ecological processes, they also are an important part of livelihoods and culture of many small stakeholders in many countries around the world. In our project, we focus on three products in three African counties as archetypical examples. To embed our work in local context, we have a close collaboration with local Universities and with local stakeholders outside of academia, ranging from (inter)governmental organisations, NGOs and farmer groups. In a process of co-creation, we have formulated research questions together with these partners, who also actively participate in the execution of the research. The PhD work is conducted by PhD candidates with strong links to the participating countries and universities. Within Wageningen, we not only work on One Health related aspects, but also include Food Technology and Women Entrepreneurship in a large project funded through the Integrated Research Fund (INREF) of Wageningen University.



Research Theme

Data and engineering science

5. Theme Data and engineering science

5.1 Summary theme Data and engineering science

The three chair groups Geo-Information Science and Remote Sensing (GRS), Mathematical and Statistical Methods (MAT) and Farm Technology (FTE) are closely collaborating within the new PE&RC theme called "Data and engineering science". Our core mission is to provide the research methods, technologies and tools that can be used to solve complex societal problems through integration of novel data acquisition tools, quantitative and qualitative modelling with domain knowledge. As a theme, we focus on further advancing the state of the art in data science and engineering methodologies for agro-environmental applications, in areas such as machine learning, machine vision and artificial intelligence, digital twins, autonomous robotics, big data and high resolution remote sensing.

For our theme the central disciplines and research areas are geo-information science, (remote) sensing, statistics, mathematics, simulation modelling, spatial analysis, software development, systems & control, and robotics. We develop, implement and support quantitative methodologies for the life and environmental sciences. Our activities involve data acquisition and handling, experimentation based on a statistical design, modelling, and technological development and application. We play a major role in data challenges encompassing the integration of multiple data sources by different types of models, the writing of professional software, and the development and implementation of decision-making technology to improve the quality of life. We are active by ourselves in our own scientific field, but we also support others within many of the WUR investment and research programmes and also external partners.

We create impact at educational, economical and societal levels by showing (potential) users that our methodology has added value for solving their quantitative questions and problems efficiently and for managing their processes optimally. Therefore, we develop and maintain a wide range of courses for different types of audiences, ranging from academic to commercial. Furthermore, we initiate and participate in many national and international research projects of a multidisciplinary nature. In these projects, we are responsible for the quantitative core. We focus not only on the techniques but also on the link with the applications and with practice. This is an important strength of operating within the Wageningen context.

In many areas of research, the sheer size and heterogeneity of data used requires more and more expertise in data science: the chair groups of the research theme are expanding in this area, with strategic planning of new data science related positions and projects. For improving our (inter)national visibility the "Open Science" strategy, which started already within our research theme several years ago, will be strengthened in the near future. For instance, papers following the principle "data with code" are supported in particular. This means scientific papers should be accompanied by open data and open software made available.

Our ambition for the future is to have an excellent reputation and to be the internationally renowned focal point in (big) data science for agro-environmental applications. We aim at extending our modelling capabilities by a closer collaboration between the participating groups in this theme addressing upcoming data science challenges central to the working area of Wageningen University in particular and society at large. Our main strength is that we understand the Wageningen application domains and can translate scientific results into practice. The ecosystem of WU is an opportunity for interdisciplinary collaborations with research groups within and outside PE&RC. Examples of activities in which we want to particularly expose the complementarity and synergy of the expertise of the participating groups for the next 6 years:

- Image-based digital plant phenotyping;
- Wageningen investment theme on "Digital twins";
- 4TU projects, the partnership with the other Dutch universities of technology;

- Data science education for the Wageningen context;

Advanced visualization to complement digital twins and data science to facilitate translational research.

5.2 Case Studies theme Data and engineering science

Case study - SESAM – Scenario Evaluation for Sustainable Agro-forestry Management

A good example of our societal involvement concerns our activities within the INREF (Interdisciplinary Research and Education Fund) programme. Some of our PhDs finished early 2021 within the EVOCA (Environmental Virtual Observations for Connective Action) project focusing on the use of life-science knowledge, digital technologies and responsible innovation concepts for addressing the pressing development challenges in crop, water, health and wildlife management in rural Africa. Recently, the SESAM project[2] started with a focus on the development of gaming approaches for better governance of the forest-water-people nexus through scenario analysis tools in three tropical continents. We coordinate ten PhD projects in this programme (either as supervisor or as (co-) promotor). These projects are run together with several chair groups within PE&RC and, for instance, also with chair groups from Social Sciences. They aim at high societal impact and integration of local actors in the research process.

[2] This is an INREF project with 15 PhD students and 2 post-docs, consisting of a highly interdisciplinary collaboration of three science groups and with partners in Indonesia, Kenya and Latin America.

Case study Image-based digital plant phenotyping

In this field expertise from GRS on (field-based) sensing, data acquisition, data analysis and use of drones is combined with expertise from FTE on (greenhouse) sensing, image analysis and robotics and Biometris' expertise on modelling to further develop this field. This is a good example of complementary expertise from the different groups. This theme started a few years ago and our strategy is to expand this theme in the future, e.g., using multiple sensors looking at multiple processes simultaneously, and linking platforms in the air with those in the field. We also plan to initiate a PE&RC discussion group for PhDs on this topic. A few new PhD studies are supervised jointly (GRS + FTE) and regularly MSc thesis students are supervised together. A summer school "Image analysis for plant phenotyping" has been organized and a PhD course "Advanced sensing approaches for plant-based in-field phenotyping" is being developed. Another example is the "Phenotyping" project using deep learning (led by MAT). Information exchange and collaboration runs also through the working group on Agro Food Robotics and the Netherlands Plant Eco-phenotyping Centre (NPEC) in which all three groups are involved. The Wageningen Agro Food Robotics community currently covers more than 100 researchers and is world leading in this field. Within this theme it is important to mention our Unmanned Aerial Remote Sensing Facility (UARSF) facility, in which we coordinate the use of drones, also called Unmanned Aerial Vehicles (UAV), in research and education for WUR. The UARSF has a range of UAVs (Figure 2) and camera's (hyperspectral, thermal, Lidar, RGB/photogrammetry, sun-induced fluorescence), takes care of the training and certification of UAV pilots and is holder of the UAV Operating Certificate for WUR.

Figure: Examples of the UARSF platforms

Using this facility, big data are exploited and machine learning techniques are developed for various applications. Currently, most Science Groups are participating within the UARSF, integrating activities of Wageningen University and Wageningen Research. In addition, joint projects with start-up companies (e.g. Van Boven Drones) allow the evaluation of innovative processing algorithms in an operational setting. This is one of the showcases enhancing our visibility as a theme.

Case study Digital Twins

A successful vehicle for increasing our research role is by participating in major WUR investment themes. "Digital twins" is one of the three investment themes of the WUR Strategic Plan 2019-2022 and it aligns with major research efforts in the EU (e.g., Shaping Europe's digital future). At the university level we already play a major role in the Digital twin project "Virtual Tomato Crops", which aims to develop a simulation model that predicts tomato plant growth in 3D. All three groups of our theme contribute with expertise like sensing, data processing, 3D modelling, genomic modelling, control and decision support (Figure 3). This project also links to NPEC.

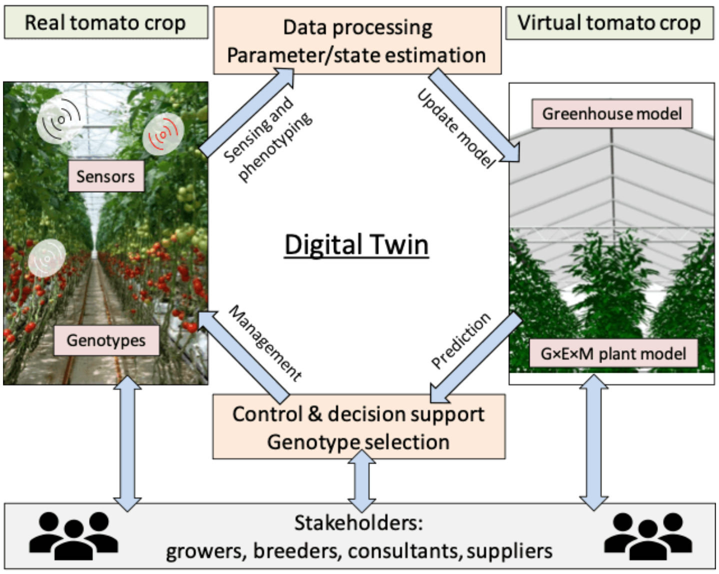


Figure: Concept map of the Virtual Tomato Crops digital twin

Our theme is also involved in another Digital twin called the Digital Future Farm, in which the nitrogen cycle on an arable or a dairy farm is studied. Our main contribution is in the field of (big) data analytics and artificial intelligence.

Currently, plans for a new investment theme on "Data science" is becoming more concrete and we are planning to take full use of this great opportunity. The personal professors on data science obviously also will play an important role.

Case study 4TU projects

Our partnership with the other Dutch universities of technology (Delft, Eindhoven and Twente) in the 4TU federation will strengthen our position as leading institution on data and engineering science for life and environment. Some project examples are:

FlexCRAFT – Cognitive Robotics for Flexible Agri-Food Technology
The FlexCRAFT programme[3] aims to develop new technologies for robots operating in agri-food environments. Robotic operation in these environments is challenging due to the presence of phenotypic variation in natural objects and different environmental/weather conditions, and occlusions, which results in partial observability of the scene. The objective is to allow robots to deal with the agri-food challenges and thereby contribute to the environmental and economic sustainability of agriculture.
The programme is a great illustration of our approach to combine good scientific research with practical use-cases in agri-food. Four generic research projects focus on the development and study of core robotic technologies needed for a complete robotic system: (P1) active perception, (P2) world modelling, (P3) planning and control, and (P4) gripping and manipulation (Figure 4). These generic technologies are integrated and evaluated in three use-case projects: greenhouse, food-processing, and food-packaging. To facilitate the valorisation of the scientific result and the knowledge transfer to industry, use-case demonstrators are being developed in close collaboration with R&D personnel from the 14 companies involved in the programme.

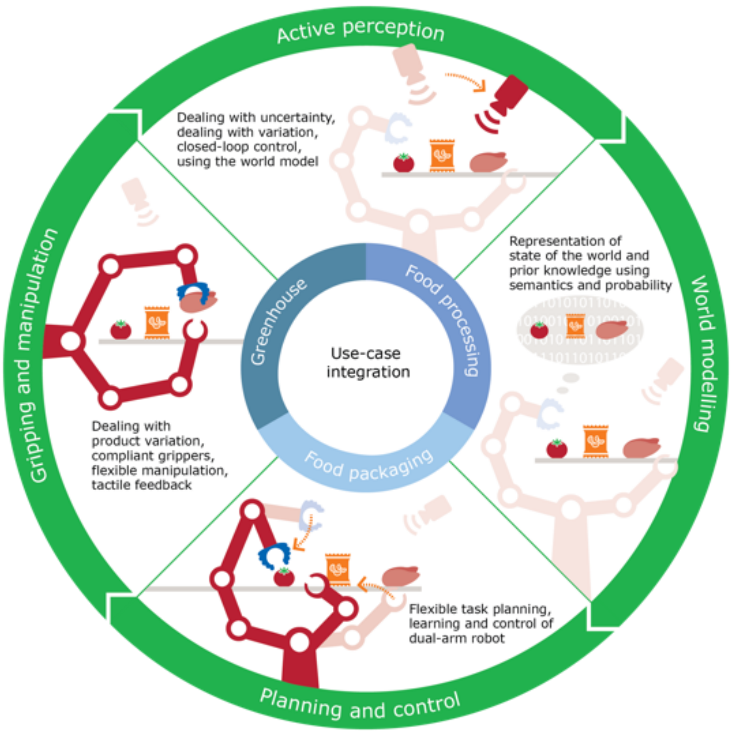


Figure:. Active perception, modelling, planning, and robotic manipulation in the FlexCRAFT programme.

This project is also linked to Soft Robotics, a collaboration within the 4TU consortium on soft-robotic technologies with application in medical (human tissues) and agricultural (fruit picking) environments.

[3] This is an NWO/TTW Perspectief programme with 10 PhD students and 3 post-docs from five different Dutch universities (WUR, TUD, TUE, UT and UvA) that started in November 2019.

DeSIRE (Designing Systems for Informed Resilience Engineering) is an extensive interdisciplinary research and capacity building programme. The DeSIRE-programme builds the capacity for the 4TU Centre for Resilience Engineering and funds its activities in the first five years. Resilience here is considered the ability of coupled social-technical-environmental systems to absorb, react, recover, adapt and reorganize with change (abrupt shocks, disruptions or chronic stresses). For Wageningen it builds upon previous research in the field of complex adaptive systems and agent-based modelling (see section 2.2.1) and has a strong link to the Social Sciences Group of WU.

Within 4TU two-year full-time post-master's programmes leading to a Professional Doctorate in Engineering (PGEng) are being developed. We plan to make enrollment in some of our courses possible as contract students.

Finally, the recent strategic alliance of WU with Eindhoven University of Technology, Utrecht University and the University Medical Center Utrecht is worthwhile mentioning in this context. This collaboration focuses on young, highly talented academics and on those subject fields that are able to generate most impact, e.g. strengthening system transitions in the fields of energy, nutrition, health and the circular society. In addition to academic collaboration among the institutions, a wide range of external partners will be involved. Significant investments will be made by this consortium during the coming decade, e.g. in health and data science.