Upsides, Downsides, and Bottlenecks of Re-diversifying the Dutch Agricultural Landscape via Intercropping

ACT Team 3360

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Image adapted from Bart Huijts

Executive summary

In a growing world population, the challenge of bringing food to the table of its human inhabitants becomes ever more complex. Agricultural production systems have turned to monocropping to meet growing demand due to the efficient and productive aspects of large-scale mechanisation. However, certain rapidly developing drawbacks to this method must be reckoned with, such as crop failure risk, biodiversity loss, and decreased resilience in a changing climate. As these issues gain prominence, so has interest in the benefits of crop diversity for agricultural systems. Intercropping, the practice of growing multiple crops simultaneously on the same field, has the potential to not only alleviate the disadvantages of monocropping, but also to harness synergetic crop traits to support a more productive, resilient, and sustainable method of agricultural production.

Our client, part of the Wageningen University and Research's joint project "New system requirements for breeding" recognises the importance of re-diversifying the agricultural landscape and envisions intercropping as promising pathway towards this goal. The client, specialising in plant breeding and aiming to develop well-adapted crop varieties for re-diversification, seeks to consider the "bigger picture" of intercropping in the Netherlands and to understand what roadblocks currently stand in the way of transition, on a biological, technological, and societal level. To provide such insight, we set to identify the current benefits & limitations of different intercropping mixtures in relation to local environments. To achieve this, we defined six research questions (RQ). We addressed the biological aspects of intercropping by establishing common intercrop combinations already used or researched in Europe (RQ1), as well identifying the underlying mechanisms which lead to the agricultural benefits of intercropping (RQ2). The most suitable intercropping combinations for local environmental factors were assessed (RQ3), and the ecological benefits of intercropping were mapped out (RQ4). On systems level, we evaluated the current technological bottlenecks for implementation (RQ5), as well as socio-economic barriers preventing a transition to a more diverse cropland by means of intercropping (RQ6).

Our research was based on an extensive, research question-based literature search supplemented with insights gained from interviews with key stakeholder groups. To provide an encompassing, multi-perspective analysis we interviewed researchers, policymakers, and farmers, both those practicing intercropping, as well as those who do not. Our output takes the form of this report, where findings are presented per research question, then summarised by a "Table of Agreements" and mapped out with a "Visual Compendium". We use these findings to present recommendations to our commissioner, and end with summarising conclusions.

For our first research question, we found the three most common intercropping combinations to be vegetable-vegetable, legume-cereal, and edible crops-agroecological/aromatic plants. Although we were unable to confidently determine the existence of "optimal" pairings, we have ascertained that "bad pairings" do exist. The biological mechanism giving rise to the agricultural benefits of intercropping (RQ2) can be explained by plant interactions which maximise complementarity and minimise competition. Beneficial interactions arise from exploiting niche spaces, encouraging facilitation, and making use of suppressive effects through cooperation. The complexities of these interaction remain poorly understood, leaving much room for discovery. Local environments can be accounted for in intercropping designs (RQ3), such as adapting to low nutrient conditions by using plant combinations with nitrogen-fixing legumes, or phosphorous-mobilising plants. Water retention can be improved with intercropping practices by increasing soil organic matter production and water availability can be bolstered with hydraulic lift effects of plants of varying rooting depth. From an ecological perspective (RQ4), a diverse crop mix, near flowering crops, attracts a variety of pollinators, increasing the rate, stability and likelihood of pollination. Birds prefer the open strip cropping fields and use hedges around the farmland to nest and feed. Agroforestry (including hedgerows) provides ecological corridors and boosts biodiversity. Low tillage and increases to soil organic matter bolsters soil biodiversity.

On a systems-based level, technological barriers (RQ5) were found to be lowest with strip cropping, however this method comes with the lowest degree of plant interaction. Famers were found to be optimistic regarding overcoming technologic limitations. GPS-aided technology was deemed indispensable, and difficulties with post-harvest sorting remain. Socioeconomically (RQ6), a major reason found for why farmers are hesitant to switch to intercropping was due to the lack of long-term vision and stability in Dutch agricultural policy. Adding to this hesitancy, farmers perceive significant risk in transitions and a lack of freedom and space to experiment with intercropping practices. Lacking communication between farmers, researcher, and policy makers was a commonly found roadblock towards progress, and farmers moving towards diverse cropping practices were burdened with overcomplicated paperwork.

Based on our extensive findings on ecological, biological, societal and technological aspects, we recommend the following to enable and encourage a transition to a diverse cropland via intercropping.

- *Agree on using the correct terminology for intercropping, and its constituents, between all parties before having a discussion.*
- *A viable first step is to switch to a wide strip strip-cropping system, with subsidies only for the transition.*
- *Make a good cropping design for well-functioning ecosystem services.*
- *Implement elements of agroforestry for improved biodiversity.*
- *Minimise tillage and leave plant residues on fields to improve soil biodiversity and health.*
- *Shorten market chains and (re)construct small-scale processing facilities.*
- *Design machinery that is suitable for strips smaller than 3 meters wide.*
- *Provide information about intercropping for society and farmers, with specific information tailored towards organic farmers.*
- *Perform further research on intercropping combinations, intercropping specific crop breeding, and crop system design.*

Intercropping can give many benefits, with the right design. To make more intercropping more feasible for farmers, some economic change is necessary in the market and supply chain. Additional research should be performed on plant breeding and complex plant relationships tailored towards intercropping.

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Introduction

Our commissioner

The case owners of this project are Wageningen Plant Research, Wageningen Livestock Research, and Wageningen Environmental Research. The project:" Circular and climate-neutral (KB-34)", focuses on the transition to a circular and climate-positive society, including many aspects such as biodiversity, climate change and artificial intelligence. Our commissioner is involved in the sub-project "New system requirements for breeding (KB-34-002-025)" which researches breeding for crop, livestock, aquatic and tree varieties. Our client specifically works on crop diversity and has been asked by the Dutch Ministry of Agriculture, Fishery, Food Security and Nature (LVVN) to study the topic of re-diversifying the Dutch agricultural landscape. To work on this topic, researchers are done on the beneficial crop variety interactions, which is the intercrop in our project.

Although the commissioner's team has a "plant breeding" oriented view on the problem (and solution), the project aims at more aspects, which not only focus on the plants themselves but also take the society, economy and technology problems into consideration. Thus, we strive to show all sides of the issue, so the drive for change in society can be tackled more efficiently and effectively. Therefore, plant breeding is not our sole focus. Our end product contains recommendations catering to the specialisation and expertise of the commissioner's team, yet also recommendations for stakeholders that are involved, such as farmers and policymakers.

Environmental crises

The world will most likely face many crises in the near future, including anthropogenically induced climate change (Hansen & Stone, 2016), various problems due to intense agriculture, such as eutrophication (Biswas Chowdhury & Zhang, 2021; Skorupka & Nosalewicz, 2021), and a decline in wild pollinators (Shivanna et al., 2020). With the increase in food demand, agriculture has shifted towards more intensive, highly productive and quality uniform crops on large areas. This inherently resulted in landscape simplification and a decrease in genetic heterogeneity. As consequence of lower plant genetic diversity and landscape simplification, crop systems may suffer more from herbivore outbreaks (Wetzel et al., 2016).

Global temperatures have already increased with ~1 °C since the Industrial Revolution (Matthews & Wynes, 2022). The Intergovernmental Panel on Climate Change (IPCC) created five different scenarios for the future temperature increase, based on how the world will develop in the near future (Strandsbjerg Tristan Pedersen et al., 2021). The Royal Dutch Meteorological Institute (KNMI) has calculated the increase in temperature for these scenarios in The Netherlands: this ranges from an increase of 0.8 °C by the year 2100, in case of a sustainable future, to 4.0 °C if the world continues using fossil fuels (van der Wiel et al., 2024). These increased temperatures are associated with an increase in extreme weather events (S. Zhou et al., 2024). For instance, for every 1 °C, the occurrence of 1-hour long precipitation extremes increases by 14% (Lenderink & van Meijgaard, 2008). Both floods (in winter) and droughts (in all seasons except winter) will occur more often and intensely in Northern Europe (Beniston et al., 2007; Dankers & Feyen, 2008; Spinoni et al., 2018). Extreme weather events influence plants and microorganisms in the soil, which in turn affects agriculture (Furtak & Wolińska, 2023).

The current way of highly industrialised, large-scale farming practiced in the Netherlands, has been shown to have far reaching negative consequences on the environment. These include phenomena like eutrophication, decrease in biodiversity, as well as emission of greenhouse gasses. Greenhouse gasses originating from arable agriculture include CO_2 from the use of internal combustion engines and decomposition of organic matter (Paustian et al., 2000), NH_4 and N_2O originating from fertilisers as well as crop residue and NO_3 from the soil (Skinner et al., 1997; Williams et al., 1992). In fact, the Netherlands is the largest emitter of N_2O in Europe per unit area (Boeckx & Van Cleemput, 2001). Surprisingly, for organically managed fields the emission rates of CO_2 and N_2O are higher than for conventional agriculture, which is explained by the higher energy inputs required, in the form of higher diesel consumption for activities like mechanical weeding (Bos et al., 2014). Greenhouse emissions originating from agricultural activities are one of the largest contributors to anthropogenically induced climate change (Williams et al., 1992).

Moreover, farmers use a high concentration of fertiliser on their farmlands, which contain nitrogen and phosphorus (Withers et al., 2014). These nutrients end up in ditches surrounding the fields, which leads to excessive algae bloom: eutrophication (Ilyas & Masih, 2018). These algae lower oxygen concentration in the water, which causes death of fish and in turn lower biodiversity (Arheimer et al., 2004). Fertiliser also contains heavy metals such as lead and cadmium (Rashmi et al., 2020), which are immobile and therefore stay present in the soil once they are applied (Salem et al., 2020). Heavy metals in agricultural soils lead to food safety hazards, diminished drink water quality, according to Tóth et al. (2016).

Furthermore, use of heavy machinery on the fields leads to soil compaction, which changes the structure in mostly the upper layer of the soil (Nawaz et al., 2013). This in turn makes it harder for plants to root, and reduces the soil porosity, which in turn limits water infiltration and reduces soil aeration (Shah et al., 2017). Finally, the number of pollinators has declined due to climate change, pesticide and herbicide use, and habitat fragmentation and loss (Ramos-Jiliberto et al., 2020; Shivanna et al., 2020). Both managed honeybee and wild pollinator populations are declining (M'Gonigle et al., 2015). Pollinators are essential for ecosystems and food production, as they pollinate respectively 85% and 80% of flowering plants (Aizen et al., 2019; Lundgren et al., 2016). In economic terms, the value of pollination was estimated at €153 billion in 2009 by (Gallai et al., 2009). Thus, pollinators are not only important for ecologic purposes but also economic.

Dutch Agriculture

Given the multitude of environmental crises linked directly to agriculture, and the ever more pressing threat of climate change makes it clear: farming needs to change. This prospect might seem a daunting task to many, as the farmer is often portrayed as stubborn, resistant to change, and primitive, with advances in agriculture quickly attributed to researchers and mechanisation (Bieleman, 2010). However, this view, historically speaking, has never been the case. Dutch farmers have always been eager to learn new things which can be seen, for example, by the high attendances of farmers in lectures from regional agricultural societies in the mid-19th century (Van Zanden, 1992), continuing into contemporary times as *milieucoöperaties* (Stuiver & Wiskerke, 2004).

Change, also, is a process farmers are well prepared to handle, having navigated technologic, economic, and social change, transitioning rapidly from a subsistence lifestyle to the highly efficient and technologically advanced agri-business of today. Perhaps the most evident historical aspect of this agility was shown during the second world war, where Dutch farmers managed to keep their population fed, despite the damaging and extraordinarily turbulent conditions they faced (Trienekens, 1985). Lastly, farmers have never been primitive: farming can be defined as "applied ecology", Zadoks (1985), where generations of farmers pass on their experiential knowledge of biological processes towards the next generation.

In the 1890's a profound development on the nature of farming came with the *scientification* of agricultural knowledge, playing a large role in creating the advanced agriculture we know today. In this transition, one could get the impression of farmers as *"technology takers"*, whereas in reality, farmers never stopped innovating and removing bottlenecks in their practice (Bieleman, 2010). An example from the modern potato sector has expert estimates claiming at least *half* of all innovation to still stem from the farmer (Bieleman, 2010; Van der Ploeg, 1987).

It is in this lens that we implore the reader to view this report. It is easy to see the farmer as the major obstruction for change, however apart from being inaccurate, this perspective is counterproductive. The history of the Dutch farmer is characterised by ceaseless innovation, cross-sector cooperation, and agility in turbulent times. While these traits may have given rise to an unsustainable system of agriculture, they are also those most needed in our current need for change. In this constructive and optimistic light, we would like to look into one pathway for change: intercropping.

Intercropping systems

Intercropping is a multiple-cropping system in which two or more crops are planted on the same field during their growing period (Dijk, 2019). There can be many types of intercropping, and the four most important and common constituents are mixed intercropping, row intercropping, strip cropping, and relay intercropping. In Figure 1, by Ecosystems United, their planting patterns are shown separately. Mixed cropping doesn't have a specific planting order, the seeds are mixed and randomly sown. Contrary to mixed intercropping, the main crop is sown in rows and usually undersown with green manure or grass. With relay intercropping, both crops are sown in rows, but at different times. So, one crop is sown when the other is already developed. This can enhance resource utilisation and allows for more efficient land use over the growing season. In strip cropping, each strip usually consists of a single crop. The strips can vary in width (3m to 21m), depending on the size of the field and the crops being cultivated. The spacing between different strips allows independent cultivation of each crop without interspecific competition while promoting complementarity (Ecosystems United, 2024). Additionally, agroforestry is also a type of intercropping which is defined as an artificially managed system containing trees, or other woody plants, alongside agricultural crops (Mosquera-Losada et al., 2009).

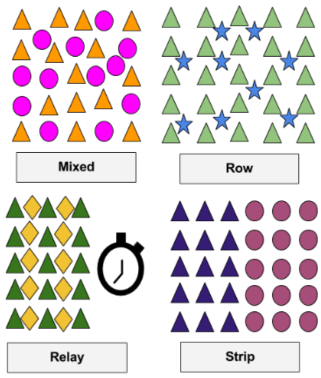

Figure 1 Different intercropping systems (Ecosystems United, 2024).

It seems that intercropping hasn't been researched for a long time, but there is a forgotten history of back in the 1890s, agronomists had already started working on intercropping in Europe and North America. Before the agriculture depends too much on fertiliser and pesticides, mix-cropping has been widely implemented for thousands of years (Homulle et al., 2022a). Harwood (2024) mentioned this practice aroused colonial agronomists' great interest during the interwar period and the beginning of the 1950s. However, after 1945, the governments focused more on high-input agriculture, and intercropping practices were marginalised until the 1970s. From the 1970s, the social and environmental consequences of industrial agriculture were under criticism, from which the intercropping practice re-emerged (Harwood, 2024).

There are a few possible benefits of intercropping, the most important and common one is increasing productivity, and land and time use efficiency. It is often achieved by overyielding because of resource partitioning, the productivity of a crop is increased in the intercropping system relative to the average yield when it is in a monoculture (Bybee-Finley & Ryan, 2018). However, there is not always an increase for all crops in intercropping. When two or more crops planted together, there will be competition between the crops. In this situation, if the dominant species has a higher yield gain than the yield loss of the dominated species, it is still defined that there is a yield advantage (Z. Wang, 2024).

Besides resource partitioning, yield increase is also partly due to pest and pathogen inhibition, which is another benefit of the intercropping system. The damages are mitigated in serval ways such as the reduction of susceptible hosts (dilution effect), physical barriers made up by resistant plants (barrier effect), and using trap and repellent crops together with the main crop (Bybee-Finley & Ryan, 2018).

In addition to the benefits related to plant production and health, the intercropping system can also help to maintain soil nutrients and health. With continuous intercropping and applying proper phosphate fertiliser, soil fertility is maintained. Even though there is no extra nitrogen fertiliser used, the total soil nitrogen amount is kept the same (Z.-G. Wang et al., 2014). Additionally, the intercropped soil can have a higher organic carbon, microbial biomass, and more active enzymes, which helps to maintain the soil health with a disease severity decline (T. Yang et al., 2020). And it can relate back to the plant benefits again, higher yield, less disease, pathogen, fewer weeds and high and stable soil nutrient, all these factors can lead to the increase of the product quality. For example, while maize is intercropped with legume, they can have on average a 10%-18% higher protein yield, compared to the monoculture of one of them under the situation of with and without extra N fertiliser (C. Li et al., 2023).

Research goal and main research question:

To contribute to the goal of re-diversifying the Dutch agricultural landscape that our commissioner set, we explored the current benefits & limitations of different intercropping mixtures on local environments to inform society about re-diversifying the agricultural landscape. This will increase knowledge for governing bodies and farmers, to help them make informed decisions. The ability to make informed decisions based on pros and cons of different cropping mixtures might help overcome socio-economic and technological bottlenecks that this goal is experiencing.

The information above lead to our main research question:

What are the current benefits & limitations of different intercropping mixtures in relation to local environments?

To answer our main research question, the following underlying research questions were answered.

Underlying research questions:

RQ1: What are the common crop combinations already used or researched in Europe for intercropping systems?

RQ2: What are the mechanisms underpinning the agricultural benefits of intercropping?

RQ3: What are the most suitable intercropping combinations for local environmental factors?

RQ4: What are the ecological benefits of intercropping?

RQ5: What are the current technological bottlenecks for intercropping in the Netherlands?

RQ6: What are the current socio-economic bottlenecks for implementing intercropping in the Netherlands?

Scope

To answer these research questions, we investigated different perspectives and aspects of the problem and present our findings in the form of this report. We performed interviews and undertook literature research; however, we did not attempt to solve challenges or pitfalls, our aim was chiefly to identify them. An agreements table was created to compile all the opinions in an organised matter (table 1). We conclude the report with a comprehensive visual overview of all interacting aspects we identified (Figure 4).

To obtain a more complete picture of the re-diversification of the Dutch agricultural landscape, we aimed to gain perspectives from research, practice, and policy. This has been done by conducting interviews with researchers, policymakers, and farmers (both conventional and those practicing intercropping). These are listed and briefly introduced below:

- **Dr.ir. Dirk van Apeldoorn** is an agronomist, researcher and teacher on intercropping at the Centre for Crop Systems Analysis at Wageningen University and Research.
- **Anne Cobben-Bertani Lopes Da Costa** works for the RVO (Netherlands Enterprise Agency) as Advisor Agro and Food chains. She is specialised in agroforestry.
- **Bei Dong, PhD.** is a researcher on intercropping who recently completed her PhD at the Centre for Crop Systems Analysis (CSA) at Wageningen UR.
- **Ing. Bart Huijts** is a part-time intercropping farmer in Voerendaal (LB) doing strip and mixed cropping. He is owner of estate Hoeve Steenenis
- **André Jurrius** is an intercropping farmer in Randwijk (GD) doing mixed cropping. Owner of Lekker lupine! and Ekoboerderij de Lingehof.
- **Ir. Johan Jurrius** is a conventional farmer in Renkum (GD). Together with his wife, Johan is the owner of Hoeve Doorwerth.
- **Ir. Edwin Tigchelaar** is an intercropping farmer in Wageningen (GD). Edwin is the owner of EET-Wageningen, an organic farm growing vegetables and crops oriented for the short-chain local market. He also works at the Hoge Born farm in Wageningen where he is also involved in vegetable farming.
- **Dr.ir. Wopke van der Werf** is associate professor in the crop and weed ecology group at the Centre for Crop Systems Analysis at Wageningen University and Research.
- **Zishen Wang, PhD.** is a researcher on intercropping who recently completed his PhD at the Centre for Crop Systems Analysis (CSA) at Wageningen UR.

Findings and analysis

RQ1 – What are the common crop combinations already used or researched in Europe for intercropping systems?

In an intercropping system, at least two crops are growing together (Dijk, 2019). The crop combination is vital they plants grow together should provide benefits. No combinations are perfect, but researchers pointed out there are bad combinations. An example was seen by intercropping farmer Tigchelaar. He had a suboptimal combination with pumpkin and lacinato kale (also known as cavolo nero), which suppressed the growth of the *cavolo nero*. Although there is no agreement whether there are perfect combinations or not, there are some common crop combinations that have been cultivated or researched in Europe. In the following part, three categories will be discussed.

Vegetable intercropping

In the interview, intercropping farmer Tigchelaar mentioned he has an intercropping with more than 30 different vegetables, such as cabbages, spinach, and pumpkin. Researcher Van Apeldoorn mentioned the vegetables intercropping such as cabbage with leek or onion. Similarly, in the PhD intercropping course from WUR, they also mentioned their research on celery and leek. These intercropping combinations can lead to high weed suppression. In western Turkey, research about cauliflower shows that there are higher cauliflower yields and profits when it is intercropped with other vegetables such as lettuce and onion (Yildirim & Guvenc, 2005). According to some Belgian farmers, another reason to intercrop celery and leek is that they can be grown at the same time with the same inter-row spacing, which is more efficient in time and space (Hondebrink et al., 2019). Another combination they mentioned is carrot and onion, which can control the damage by carrot flies.

Legumes and cereals intercropping

Besides vegetable intercropping, another common combination, mentioned by researchers Wang and Dong, and intercropping farmers A. Jurrius and Huijts, is legumes and cereals. For legumes, crops such as faba bean, lupine, and pea are used. Cereals include wheat, maize, and oats. This is a very traditional and common combination that has been implemented and researched a lot all over the world. In Europe, especially West Europe, which has a temperate and humid climate, legumes are also available to be intercropped with brassicas (Brassicaceae Juss.). The examples are rapeseed with faba bean, and fodder cabbage (*Brassica oleracea* L.) with common vetch. The research also shows the possibility of intercropping legumes, cereal, and brassicas together such as the combination of pea, wheat, and rapeseed (Mikić et al., 2012).

Researchers even argued that brassicas are a better choice for intercropping with legumes than cereals as barley since it is such a strong competitor that it reduces the nitrogen fixation efficiency (Mikić et al., 2012). Another research shows more efficient legumes intercropping combinations with other vegetables. Intercropping cabbages or carrots with faba beans can increase the yields of these two vegetables (Lepse et al., 2017) . At the same time, onion is not a good choice to intercrop with faba bean. Compared to the other two vegetables, even though onion increases yields of faba bean the most, it comes at the expense of a very low onion yield (Lepse et al., 2017). Not only legumes but cereals can be also intercropped with vegetables. In Belgium, farmers grow maize and courgette together so that maize can work as a windscreen to avoid courgette wind damage (Hondebrink et al., 2019). They also do wheat and potato intercropping so that they can achieve mechanised weeding.

Edible crops with non-edible crops

In addition to edible crops and products, grasses have been used often in intercropping systems. Except in Eastern and Southern Europe, there is a long tradition in Europe that clover is intercropped with other grasses like ryegrass (*Lolium* spp.) and timothy (*Phleum pratense* L.) (Mikić et al., 2012). The intercropping farmer A. Jurrius also mentioned he grows cereal with grass, in a combination such as maize with clover underneath. In Latvia, intercropping vegetable crops with agroecological service plants and aromatic plants has been found to increase vegetable yields (Lepse & Zeipiņa, 2023). The variety combinations leading to positive results mentioned here are cabbage with marigold, sage and lavender, and sage with carrot.

Other insights

In the paper "Can legume companion plants control weeds without decreasing crop yield? A meta-analysis", the researchers mentioned that they also used "intercropping" as a keyword to find relative literature (Verret et al., 2017). This is an interesting way to think about whether there are similarities between intercropping and companion planting. Companion plants are grown together with contrasting and/or complementary characteristics (Mayer, 2011). For example, aromatic plants that drive away pests are paired with non-aromatic plants. Under the same principle, there is an intercropping method called "push-pull", which is shown in Figure 2 (Stenberg et al., 2015). So, some researchers also stated that when companion planting is implemented for agricultural production, it can be considered a subset of intercropping (Ecosystems United, 2024). Thus, to some extent, the companion planting combinations can be used in intercropping systems or at least work as a reference.

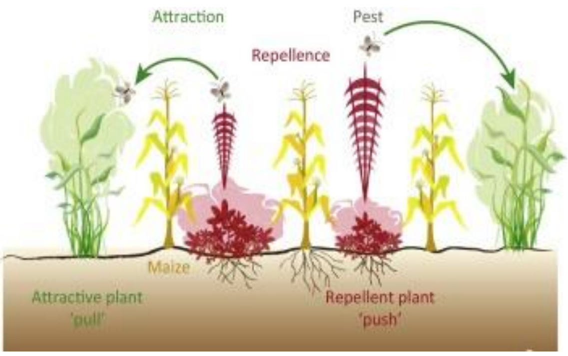

Figure 2: "Push-pull" system in intercropping

Summary

To conclude, there are three common crop combinations that has been used or researched in Europe, which are vegetable intercropping, legume and cereals and edible plants with non-edible plants. They are not separate categories since there are overlaps such as vegetables are also available to intercropped together with legumes. The non-edible plants are either agroecological service plants or aromatic plants that help with the ecosystem benefits or the growth of the main crop in the field. Since there are similarities between companion planting and intercropping, what have been used in companion planting can be a reference while thinking about the crop combination in intercropping system.

RQ2 – What are the mechanisms underpinning the agricultural benefits of intercropping?

"Intercropping" can be defined as growing two or more crops on the same field. However, this definition is too broad to truly discuss the mechanisms of intercropping, as it is the specific implementation of the "two or more crops" which determines the outcome. The broad definitions of intercropping and styles that fall under that umbrella, including the broader term "crop diversification" is a prevalent issue in research, and practice, which hinders comparability and generalisation of findings in the field (Hufnagel et al., 2020). For example, when asked about crop combinations, Van Apeldoorn, a strip cropping researcher, stated that a specific crop combination does not matter nearly as much as stepping away from the monoculture through either a simple crop rotation or strip cropping. In contrast, row/relay researchers Wang and Dong both wrote entire theses on the effects of different crop combinations. Therefore, it is important to discuss the various scales and setups of intercropping systems, and what benefits and drawbacks are to be found on the spectrum of implementations.

Definition and Scale Dependency

The spectrum of intercropping implementations ranges from lower to higher degrees of spatial (and temporal) heterogeneity. Higher degrees of heterogeneity give rise to increasing plant interaction, from where the main benefits of intercropping stem. On the other hand, increased heterogeneity makes mechanisation increasingly difficult and adds complexity to management. Thus, as plant interaction goes up, efficiency tends to go down. The challenge in implementing the right intercropping setup lies in finding the optimal balance between the two. On the lower end of the spectrum we find *strip cropping*, the form of intercropping which most closely resembles the monoculture. The main benefits of strip cropping are the gains in biodiversity and pest / disease prevention (Homulle et al., 2022b), while maintaining the ability to use conventional mechanisation to manage the field, thus retaining relatively high labour efficiency and remaining easy to implement. The narrower the strips, the more plant interactions are to be expected at the cost of mechanisation, until strips are just one plant row across, at which point one has reached *row intercropping*.

Relay intercropping further increases the resource use efficiency of row intercropping by additionally exploiting the temporal dimension (i.e. by combining early and late sown crops). The maximum level of heterogeneity is reached with *mixed intercropping*, where complete mixing of multiple crops allows the benefits of plant interactions to be fully utilised, though with added challenges for management, such as necessitating post-harvest sorting. The extensively mentioned "plant interactions" from which the benefits of intercropping arise is a broad term in itself but must be understood to properly optimise the system. In general, this is achieved when competition is minimised, while complementarity is maximised.

Complementarity

The mere act of planting a variety of species or cultivars on the same field provides more yield stability through asset diversification (and compensation) (Raseduzzaman & Jensen, 2017), however the added value of intercropping truly comes into play when *complementarity is* exploited and optimised. Complementarity can be understood through three distinct categories: Niche space, Facilitation, and Suppression.

Niche space

Niche space complementarity occurs when intercropped plants reduce their competition for resources by occupying different niches, either spatially, temporally, or in terms of resource specialisation (Ehrmann & Ritz, 2014). Spatial niche differentiation can be utilised by combining shallow and deep-rooted species and exploiting root plasticity (Gebru, 2015; Hassan et al., 2021), some species tend to practice root avoidance strategies, whereas others aggregate roots when planted next to a different species. If species and cultivars are chosen correctly, severe competition can be avoided and nutrient uptake can even be enhanced (Schiffers et al., 2011).

Aboveground, spatial niche differentiation can be achieved by planting tall crops and short crops together for more efficient utilisation of incoming radiation (Awal et al., 2006; Gou et al., 2017; J. Zhu et al., 2015). Combining C_3 and C_4 crops in this manner (Y. Yang, 2016) is a promising tactic, and one interviewees Wang and Dong share interest in researching further. Tall and short crops together alter the canopy structure, thus changing the incoming light quantity and quality (i.e. red to far-red light ratio) for intercropped plants in comparison to monocropping. Altering plant morphological responses to such changes through breeding efforts could be a viable pursuit to further increase the light use efficiency of intercropping techniques (Justes et al., 2021). This aspect was mentioned by Dong and Wang during their interview, as their strip cropping design used monocrop cultivars for their intercropping experiments, likely not optimised for the altered canopy structure.

Further enhancing radiation capture can be achieved by utilising the temporal dimension of niche space complementarity through use of relay intercropping (Yu et al., 2015). Essentially, this is achieved by early sowing of a suitable plant in rows, followed by a later sowing of a companion plant in the inter-row space. The later sown crop is harvested sometime after the initial crop, practically extending the growing season beyond what would have been possible with a monocrop system. The periods of time where each crop is alone on the field allow competition-less growth, resulting in yields that outperform regular monocropping and even non-relay intercropping (Z. Wang, 2024). The potential yield and efficiency benefits of relay intercropping was one of the main findings of the PhD projects of Dong & Wang, and they suggest it could be a good measure for transitioning towards lower fertiliser inputs while maintaining high yield (in the Netherlands). Additionally, the varying developmental rates and stages of different plants can be taken advantage of with relay intercropping, and possibly further optimised through breeding, such as selecting for vigorous root growth and nutrient uptake after the initial crop has been harvested, likely the aspect underpinning the success of relay intercropping (Homulle et al., 2022b).

The last niche space to consider is the resource niche, where plants access different pools of nutrients, commonly different forms of nitrogen (NO_3^-, NH_4^+, N_2) (Boudsocq et al., 2012; Britto & Kronzucker, 2013; Liu et al., 2020). A common pairing to exploit this niche is planting an N_2-fixing legume with a highly N-competitive species, such as wheat, thereby also forcing the legume to produce more its atmospherically sourced nitrogen (F. Fan et al., 2006). Huijts shared his experience with this method and found the protein content of his conventionally managed wheat to jump from a monocropped 13.6% to 17.1% when intercropped with Faba Bean (legume) under a low input management. The resource niche differentiation is most influential in full mixture intercropping, but also in effect at borders in strip/row intercropping systems, however all the mechanisms behind it are not yet well understood, limiting the degree to which it can be further optimised (Stomph et al., 2020).

Facilitation

Where niche space complementarity mainly arises from the avoidance of plant interaction (from usage of different resource pools), complementarity through facilitation entirely depends on it, however it is usually a one-sided process (Valiente-Banuet et al., 2006). Plants of differing species (although usually legume towards non-legume) can share nitrogen (Frankow-Lindberg & Dahlin, 2013; Pirhofer-Walzl et al., 2012) directly via root exudates (Homulle et al., 2022b), over longer distances with mycorrhizal hyphal networks (Selosse et al., 2006; Van Der Heijden & Horton, 2009), or decomposition of roots or exudates (Tsialtas et al., 2018). The amount of transferred nitrogen can be as high (or low) as 0-73% (Thilakarathna, McElroy, et al., 2016), although more reasonable estimates place it 0-15% (Homulle et al., 2022b; Peoples et al., 2015).

Species pairing is important to consider, as proper pairing can even reverse the effect and cause the non-legume partner to facilitate the legume in N-fixation (F. Fan et al., 2006; Homulle et al., 2022b; Hu et al., 2021; B. Li et al., 2016). The benefits of this effect (yield, protein content) was experienced by multiple interviewed intercropping farmers. The degree of N transfer depends on a myriad of factors (Islam & Adjesiwor, 2018), including species genotype and cultivar combinations, as well as seeding ratios (McElroy et al., 2016; Thilakarathna, Papadopoulos, et al., 2016), correctly chosen mycorrhiza strains (Fujita et al., 2014; Shantharam & Mattoo, 1997). Adequate soil moisture levels, high enough to prevent N-mineralisation (Mhadhbi et al., 2011), but low enough to avoid anaerobic conditions, leading to gaseous N loss in the form of N_2O are important as well (Tisdale et al., 1985). Additionally, light conditions, as mentioned by interviewee Dong, temperature (Ofosu-Budu et al., 1992) and dark treatment (Pérez Guerra et al., 2010) (especially important for grass/legume systems or variable height setups (Thilakarathna, McElroy, et al., 2016) play into this complex process (Homulle et al., 2022b).

Nutrient sharing extends to Phosphorous as well, where improved nutrient uptake can be derived from combining a P-mobilising species with a non-P-mobilising species (Homulle et al., 2022b; Tang et al., 2021), for example maize and faba bean (C. Li et al., 2016), white lupin and wheat (Cu et al., 2005), or chickpea and maize (LI et al., 2004). Unlike nitrogen, phosphorus cannot be transported longer distances via mycorrhiza, thus spatial considerations are needed to make full use of facilitation of P-uptake, favouring the fully mixed over strip cropping (Giles et al., 2018; Homulle et al., 2022b).

Water uptake is another aspect which can be facilitated by species pairings. Deep rooted and shallow rooted crop pairings are examples of spatial niche differentiation but can also be classed as facilitation if the deep roots offer more water to the shallow roots by means of hydraulic lift (Homulle et al., 2022b; Richards & Caldwell, 1987). This effect can also be created by mycorrhiza (Singh et al., 2019). Increases to local soil moisture also mobilises nutrients, yielding additional benefits to nutrient uptake, as found in, for example, deep-shallow legume forage systems (Pang et al., 2013), or pearl millet and rice (Izumi et al., 2018).

Suppression

Intercropping systems can make it harder for weeds to invade and establish themselves through mechanisms such as increased spatial and temporal competition and more complete resource usage (Stomph et al., 2020; van Ruijven et al., 2003). Belowground, pests and disease are suppressed through reduced host plant density, direct inhibition, and enhanced microbial abundance, an effect corroborated by interviewed organic intercropping farmer, A. Jurrius. Reducing host plant density has been shown to reduce pest pressure (Ehrmann & Ritz, 2014; Mommer et al., 2018; Ratnadass et al., 2012), most effective with full mixture intercropping. Additionally creating physical barriers can lead to strong reductions in disease, an effect of high importance to our interviewees (Huijts, J. Jurrius, Tigchelaar), and backed up by research (Ehrmann & Ritz, 2014; S. Zhu & Morel, 2018). An example pairing, tomato with forage grass, led to a 40-50% reduction in tomato stem rot (Y. Zhou et al., 2019). The intercropping pattern most suited for this effect is the strip or row method.

Another suppressing effect is the direct inhibition of pests and disease when plants release root exudates to protect themselves. This effect extends beyond the releasing plant species, to other plants species nearby (Ehrmann & Ritz, 2014). As this effect requires species interaction, the mixed intercropping pattern is best suited to take advantage of this suppression pathway. Examples of suitable pairings include tomato, mulberry, or soybean when mixed with marigold (El-Hamawi et al., 2004; Hooks et al., 2010; Tsay et al., 2004).

Lastly, higher crop diversity from intercropping leads to increased microbial diversity and abundance (Kowalchuk et al., 2002), which essentially increases the chances of the presence of beneficial strains (those that are hostile to plant pathogens) (Dai et al., 2013; de Medeiros et al., 2019; Homulle et al., 2022b; Ratnadass et al., 2012), for example pairing cucumber with a (specific) cultivar of garlic (Xiao et al., 2012).

Traits to improve

Modern crop cultivars have led to large improvements in yield and other agronomic factors, yet these crops have been bred for use in monoculture and have not been optimised for the growth conditions of intercropping (Bourke et al., 2021; Lithourgidis et al., 2011). Thus, improvements to yield and other factors already achieved with intercropping relative to monocropping are likely far from their true potential (Wang & Dong, Interview). A major issue with improvements to plant "ideotypes" (trait-based breeding) (Bourke et al., 2021) is that there is no clear definition on which traits should be targeted for more positive interactions, especially those relating to below-ground processes. Homulle et al. (2022b) recommends a framework where first the desired outcome is determined (such as improvements to yield, quality, resource use efficiency, pest suppression), followed by identifying the complementarity traits underpinning this goal (Louarn et al., 2020). Some example targets include root plasticity to optimise spatial niche differentiation / facilitation, nutrient niche differentiation (Homulle et al., 2022b), (early) root vigour, emergence, and rooting depth optimised for local water and nutrient conditions (A.V. et al., 2019; Voss-Fels et al., 2018). Clearly, this is a complex task, as multiple traits need to be targeted in multiple species to get optimal combinations right (Homulle et al., 2022b). As a whole, this field remains poorly understood, especially with regards to root processes (Faget et al., 2013; Weemstra et al., 2016), and mycorrhizae, the latter of which will likely have a heightened role due to the healthier soil environment brought about from intercropping practices (Homulle et al., 2022b), and which is also likely to be a genetically controllable factor (Bourke et al., 2021).

Summary

The agronomic gains of intercropping depend on a combination of factors: the method, scale (both spatially and temporally), and the crops/cultivars implemented. Broadly speaking, the degree to which plant complementarity, facilitation, and compensation can be promoted while minimising competition determines the benefits (Justes et al., 2021). Lacking cultivars designed specifically for intercropping leave untapped potential for optimising intercropping systems. A more complete understanding of plant interaction mechanisms is critical towards targeting certain crop "ideotypes" through plant breeding, which will be essential in promoting the adoption of intercropping practices for sustainable agriculture (Homulle et al., 2022b).

If designed and optimised correctly, farmers can expect gains to their yields (as experienced by A. Jurrius, Huijts), more yield stability (experienced by Huijts) in a changing climate, easier compliance with agricultural policy (experienced by A. Jurrius) as well as health benefits due to less requirements for inputs such as fertiliser, pesticides, herbicides, and fungicides (as brought up by Van der Werf).

RQ3 – What are the most suitable crop combinations for local environmental factors in intercropping system?

In the interview with Wang, it came to light that for all suitable intercropping combinations "The limiting resource of the field needs to be identified, and then a suitable management should be practiced". So, during this chapter insight will be given about suitable combinations (or practices) for the possible limiting resources.

Mostly we looked at systems with two crops, for simplification purposes. There are of course many possibilities with more than one combination, however explaining the reasoning behind pairings is simpler with only two crops in a pairing or mix. Mixes between the theoretical combinations for certain environments, might be more applicable to strip-cropping farmers that want more than two crops in their rows, if they suffer from more than one of the named limitations.

This chapter includes combinations of which some are more theoretical than others. It was aimed to stick to examples that include practical pairings as well. Overall breeding for perfect, or even in general, intercropping combinations is not yet developed and/or under researched. Generally, systems should be adapted to local environments for as far as possible. Both of these statements were confirmed by interviewed researchers and farmers.

Poor soil environment

To increase soil organic matter (SOM) Van Apeldoorn mentioned the use of a syntropic farming method, which is not quite suited for Dutch agriculture. Generally, trees and shrubs are planted and subsequently cut down and burned. Afterwards, the remains are ploughed into the soil to increase the carbon content and SOM. Reshaping poor soils might benefit from this approach, however, soils found in the Netherlands are not depleted to the level of which we consider this tactic to be necessary.

Mixed cropping farmer A. Jurrius found that when growing clover under cereals in a mixed cropping system the SOM goes up, beneficial for the cash crop: cereal. J. Jurrius, a conventional famer with biodiversity strips, uses plants which are part of his green manure mixture to increase SOM during the off-season, to help build a healthier soil and increase water retention. Biodiversity strips are borders, containing a mix of native flowers, around an agricultural field which are subsidised by the government.

Increased Soil Organic Carbon (part of SOM) has been observed for intercropping relative to monocropping of the constituent plants. SOC increased by 17.75 % according to a meta-analysis done by (S. Li et al., 2024). Increasing SOC and SOM has been linked to soil health ecosystem services such as increasing nitrogen supply, and plant-available water-holding capacity (Meyer et al., 2015). Therefore, intercropping in itself, but maybe more so, intercropping with a cash crop and a crop that increases SOM can increase soil health in the long term, yet still generate revenue for the farmer in the short term.

Another carbon-binding, SOC improving revenue stream for farmers has been proposed: selling carbon credits to producers of higher amounts of greenhouse gasses. This revenue stream is still in its infancy and further possibilities still need to be explored (Lokuge & Anders, 2022).

Low N or P nutrient environment

In a low nutrient environment, such as in depleted soils or low input systems such as organic farming, farmers search for alternative sources of nutrients. Excessive nutrient leaching/drainage must be prevented in non-growing seasons, otherwise these nutrients are not available in the coming growing season (Wyland et al., 1996).

A. Jurrius combatted nutrient leaching by using grasses as green manure in the off-season. Since 2001 it is mandated by the government to use a catch crop on sandy or Loess soils, to prevent nutrient leaching (Ligtvoet, 2006). Combatting nutrient leaching is also common for non-mixed cropping farmers such as J. Jurrius, who used clover as an under sown crop for cereals, which in turn increases N fixation. Wang acknowledges this and stressed the importance of positive root interactions by picking the suitable crop combinations, such as clover and cereals, as these are more beneficial for nitrogen availability being less limiting.

In a low N environment, or low N input cropping system, intercropping with legumes will increase N nutrient availability. This reduces the need for artificial N fertiliser (Jensen et al., 2020), which increases sustainability and independence of the farmer. In a low N environment, or low N input cropping system, intercropping with legumes will increase N nutrient availability. This reduces the need for artificial N fertiliser (Jensen et al., 2020), which increases sustainability and independence of the farmer. White lupin (*Lupinus albus L.)* has P mobilising capabilities, from which wheat can benefit, since wheat has lower P mobilising capabilities, but it is a cash crop compared to lupin (Kamh et al., 1999). Growing them in a mixture or small strips, or even yearly rotation should be beneficial to the P nutrient needs of the wheat.

Low water/deep groundwater table environment, or dry environments

During the interviews no mention was made of potential benefits of intercropping in dry environments, or environments with a deep/low groundwater table.

In literature it was found that certain combinations of crops could improve the hydraulic lift in the soil. This means that plants with deep rooting systems 'pull up' the water so it reaches the other crops with shallow rooting systems, as demonstrated by Sekiya & Yano (2004) where pigeon pea supplied water to maize through hydraulic lift. So, a combination of a cash crop with shallow rooting systems and a 'working' crop with a deeper rooting system could provide the cash crop with sufficient water during dry periods without having to irrigate, or when irrigating is not an option.

Low groundwater tables and quick drainage of water are more common in sandy soils than in clay soils. Groundwater tables are more dependent on local environment, such as temperature and rainfall, but soil type does influence the groundwater tables (Cleophas et al., 2022).

Implementing a crop for increased hydraulic lift is of course limited by how low the groundwater table is. J. Jurrius farms on sandy soil with a groundwater table 20-30m below the field, no plants or trees will be able to 'pull up' the water that far down. This is likely why he indicated that he sees bottlenecks with irrigation in a diverse cropping system. In a clay soil, or with a higher groundwater table the hydraulic lift combination of crops can be beneficial.

For a dry environment with low atmospheric relative humidity Van Apeldoorn mentioned using hedgerows or trees to increase relative humidity in up to 10 times the height of the trees. This could be used by farmers that suffer from short and extreme dry periods during their crop season, to mitigate the stresses on the crops. The exact scale that is mentioned was not verifiable in literature, but that trees can increase air humidity in their surroundings is confirmed by (Georgi & Zafiriadis, 2006).

Low light environment

In a low light environment, the type of intercropping might be helpful in assisting with negating the shortcomings. Relay intercropping is a possible solution when the farmer thinks that the biggest limitation in his cropping system is the light use efficiency. According to Wang, and his thesis, having an early crop that needs light early, and a late crop that needs light at a later moment is beneficial, as there is no competition for light during moments that the individual crops need it the most. This has resulted in up to 22% more land use efficiency (Z. Wang et al., 2023). However, the full potential of this system with lower light use competition has not been reached, since there are not yet crops that are bred for this light use efficiency complementarity in intercropping, according to Wang and Dong.

Shading and competition for light by intercropped plants was seen as a major drawback by an interviewed conventional farmer, J. Jurrius, which was one of the biggest reasons that he thought that adopting strip-cropping was not feasible for him. Additionally, the variability in shading / light competition within the field was said to have led to variability in the final harvested crop. Less homogenous products are given less value in the current market.

Summary

Poor soils would benefit from crop mixes that increase SOM, and SOC. For low nutrient input environments crop mixes including crops such as legumes, which bind or mobilise N or P, are beneficial. Relatively low groundwater tables can be negated by incorporating a crop that utilises hydraulic lift to draw up the available water from deeper below surface. In dry humidity environments, hedges or treelines can mitigate the low relative atmospheric humidity. When the limiting resource is light, an agricultural management switch towards relay intercropping is potentially worthwhile.

RQ4 – What are the ecological benefits of intercropping?

As mentioned earlier, intercropping can give many benefits, such as less need for fertiliser and pesticides and a more aesthetic landscape. These advantages do not only benefit the farmer, but also provide a more natural habitat and improve the ecological status of the area. Intercropping improves ecosystems services, increases biodiversity, and improves the soil health. These effects can be seen in Figure 3 below, and, along with other effects, are further elaborated on below in order to answer the following research question: *What are the ecological benefits of intercropping?*

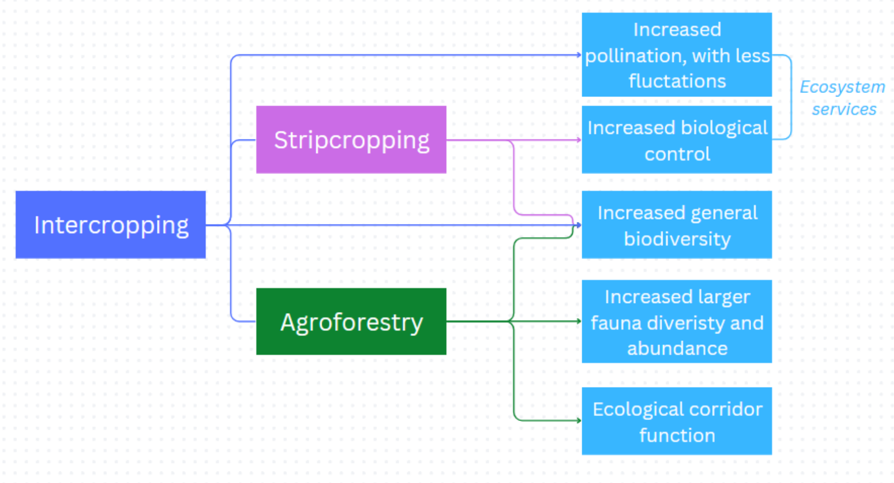

Figure 3: Effects of intercropping, with effects of agroforestry and strip cropping further specified, on different ecological functions.

Increased ecosystem services

Ecosystem services are defined as "benefits nature provides" (Bennett et al., 2009). This can be materialistic (food, water), non-materialistic (place for recreation) and regulating (flood protection, pollination, seed dispersal) (Bennett et al., 2009; Kremen et al., 2007). Intercropping can provide some of these ecosystem services, such as pollination and pest control (Lichtenberg et al., 2017).

Pollination is an essential ecosystem service, as 75% of all crops and 87% of all flowering plant species depend on natural pollination in order to produce fruits and/or seeds (Ponisio et al., 2016). Intercropping can improve the living conditions for these essential pollinators, as the diversity and abundance of insects is higher in fields with low fertiliser and pesticide use and in fields with increased plant diversity (Lichtenberg et al., 2017), both of which can be the case for intercropping fields. The use of these chemicals lower insect populations (Järvinen et al., 2022; Ramos et al., 2018), and is, after habitat loss, the most important driver of insect population decline (Sánchez-Bayo & Wyckhuys, 2019).

Important to consider is that some pollinators can travel further than others to forage: solitary wild bees can forage for flowers up to 750 m away, bumblebees between 1750-3000 m (Westphal et al., 2003), and honeybees can cover 2.5 to 3 km (Steffan-Dewenter et al., 2002). A more diverse plant mixture can allow the agricultural field to cover more ecological niches with regard to food availability, therefore leading to a more diverse pollinator scene (Järvinen et al., 2022). Hereby, the dominant pollinator species in monoculture fields become less abundant with intercropping, leaving room for rare species (Lichtenberg et al., 2017), and thereby increasing the functional diversity (Järvinen et al., 2022): the number of different species present in an ecosystem (Martin et al., 2019). With a higher functional diversity, pollination increases, has less fluctuations and is more resilient (Järvinen et al., 2022).

The biological control of pest species is also more present in strip cropping fields, as mentioned by Cobben. For example, one strip may be host of a predatory arthropod species of a pest species in the strip next to it, so this is essential to keep in mind while designing the different strips. A German experiment with strips of winter wheat and oilseed rape of 27-36 m wide studied predatory carabid beetles and spiders. The study revealed a decrease of 50% of pest species in winter wheat strips, and a 20% decrease in oilseed rape strips when compared to monocultures (Alarcón-Segura et al., 2022). This effect has also been observed in the 21 m wide strips of Huijts. A faba bean aphid was present in his crops, but predatory ladybugs from surrounding strips ate all of the aphids, which meant he did not have to use pesticides.

Increased biodiversity

Mixed cropping systems do not solely have a positive influence on pollinators but improve general biodiversity of all animals in/around the agricultural fields (Wenda-Piesik & Synowiec, 2021). Specifically, strip cropping attracts meadow birds such as the oystercatcher, lapwing and the meadow pipit (Godijn et al., 2022). Tigchelaar stresses that the smaller a strip is, the more biodiversity increases. A. Jurrius already sees a large effect at strips of 12 m in bird abundancy and diversity. Van Apeldoorn has also studied the effects of strip cropping on birds by performing questionnaires with Dutch farmers. His findings indicate, when comparing monocultures with strip cropping, strip cropping leads to an increase in bird abundancy, and a 50% increase in bird diversity.

When hedges are placed between agricultural fields (Lichtenberg et al., 2017), terrestrial biodiversity greatly improves. They provide food and act as an ecological corridor for arthropods and larger fauna such as hedgehogs and birds (Lichtenberg et al., 2017; Yarnell & Pettett, 2020). Farmland birds use the hedges to nest and feed, while woodland birds use them as ecological corridors between forests (Batáry et al., 2012). Strip cropping farmer Huijts has placed hedge rows between his farmland and has experiences greater bird diversity.

Not only hedges, but agroforestry in general can improve biodiversity (Torralba et al., 2016). Cobben has stated that birds, arthropods and even larger animals such as deer and badgers can be found closely within/around agroforestry plots. This was also observed in a study performed on food forest Ketelbroek in Groesbeek (Breidenbach, 2017). Biodiversity in the food forest itself and in the neighbouring Natura2000 area De Bruuk was measured. Abundance and composition of breeding birds, carabid beetles and macro-moths were determined and compared. The abundance of species showed similar numbers, with the Ketelbroek food forest having a slightly higher number of different species. However, species composition greatly differed, which is most likely due to local habitat differences. This shows the importance of agroforestry, as it provides a habitat for different species than nature areas.

Maintain soil health

Finally, soil quality and biodiversity improve under an intercropping system (Cong et al., 2015; Maitra & Ray, 2019). Soil organisms perform better with a diverse crop choice in the fields, grass/flower strips around the field and reduced tillage (Crittenden et al., 2015). Especially tillage of the soil disrupts the earthworm specie groups and collembolans through mechanical damage, change in organic matter and soil water content (van Capelle et al., 2012). Anecic earthworms, important for water infiltration and creating deep pores in the soil (Keith & Robinson, 2012), are declining in number due to less crop residues left on the fields to feed on and are very sensitive to soil compacting (Crittenden et al., 2015). Soil fauna are also important as they increase the humus formation in the soil and excrete nitrogen (N) (K.-H. Wang et al., 2011). Under N-rich conditions, they can even increase plant N uptake (Laakso et al., 2000). Moreover, conditions for microbial communities improve with intercropping. Planting legumes promotes beneficial bacteria, such as *Rhizobium* and *Arthrobacter simplex,* which provide benefits such as increased plant growth (Maitra & Ray, 2019).

Wheat-legume intercropping systems reduce tillage and increase food supply for fauna. An experiment with wheat-clover intercropping showed the abundance and biomass of earthworms increased by 271% and 326% respectively when compared to wheat monoculture (Schmidt et al., 2003). Cobben has also seen that implementing agroforestry leads to increased soil fauna biodiversity. The litter layer of the trees, combined with the different crops and a lack of tilling, gives rise to a high organic matter content.

Summary

To summarise, intercropping brings many ecological benefits. It can increase the ecosystem services, specifically pollination and biological control. Moreover, it can increase faunal biodiversity, in all trophic levels. Finally, it can improve the soil health and its biodiversity. Agroforestry improves biodiversity and provides an ecological corridor function for animals, while strip cropping increases biological control and increases the biodiversity of fauna requiring open landscapes.

RQ5 – What are the current technological bottlenecks for intercropping in the Netherlands?

During this study it was found that the opinions are divided regarding the technological limitations for diversification of the Dutch agricultural landscape through intercropping. According to multiple farmers, intercropping can be adopted without many problems when the design of the cropping system is well thought through. They all agreed that strip cropping can be implemented without requiring specialised machinery when one adheres to common working widths of existing (tractor-drawn) implements, which are usually multiples of 3 metres. As most farmers choose a cropping system that will fit the machinery they already own, they do not experience major troubles in this area. Huijts for example, uses strips of 21 metres wide. This way, his contractor is able to use the current machinery as this is the width of the sprayer booms.

Strip width

It is generally accepted that smaller strips have more benefits in terms of biodiversity and beneficial plant-plant relations (van Oort et al., 2020). However, adoption of smaller strips leads to lower time efficiency, as more turning at the headlands is required, as per the interview with Huijts. When adopting a strip cropping system with uncommon strip widths, one would need to invest in custom-made machinery, resulting in costly investments in research and development of these implements.

However, from the literature and the interviews with the researchers, a different picture is painted. From the results of an international survey conducted on many farmers from all over Europe technological difficulties are stated to be one of the main challenges farmers face when converting their operations towards intercropping practices. In this study, a need was expressed for new state-of-the-art machinery to be developed, that can deal with the heterogeneous nature of intercropping systems and is able to recognise the crops using sensors or camera technology (Hondebrink et al., 2019).

Many farmers are interested in intercropping due to its potential benefits regarding increased pest and disease resilience due to increased biodiversity as well as a potential increase in crop performance. But they are unsure about whether the practice can be scaled up to meet the demands of the industrialised large-scale agriculture that is commonly practiced by them without losing efficiency (Hondebrink et al., 2019). When selecting a suitable cropping system, farmers in the Netherlands value efficiency, a point that was made during our interviews as well.

GPS-guidance

The only thing that was indispensable when practising strip cropping according to the interviewees (i.e. Huijts from Limburg, Tigchelaar from Hoge Born) was having a GPS guidance system on the tractor to closely follow the strips when working the fields. This is supported by literature, namely by one of the respondents to the previously mentioned survey who is a flower farmer in the Netherlands. He stressed the importance of permanent location of the strips, as shifting the strip even by a small amount was noticeable in the crop during the next year (Hondebrink et al., 2019).

Mechanisation

With mixed cropping the two different crops are harvested together. Depending on if the product is for human consumption, post-harvest separation of the two different crops is necessary. This can be achieved via sieving of the product. However, when the goal is animal fodder, the product can sometimes be combined, and thus sieving is not necessary. This was explained by A. Jurrius. One study has also pointed at the costs of the sorting process and the challenges associated with the proper separation of the different crops. Also, the storage of the crops was found to be one of the main concerns under co-operatives and farmers (Fares & Mamine, 2023). With strip cropping, these concerns are less present, as one can harvest the crops separately, removing the need for post-harvest sorting. So, with the clever design of the cropping system, the entire growing process from seedbed preparation to the harvesting of the crops can be mechanised, depending on the system and the type of crops grown.

Other challenges lie in the fact that current agricultural machines used in the Netherlands is geared towards high efficiency for large scale agriculture. These machines are able to cover a lot of area in a given amount of time and often feature large working widths. This is for example the case with irrigation (mostly sprinkler technology) and fertilisation technology (often based on the principle of broadcasting), according to Van Apeldoorn. However, these issues can be resolved by implementation of a drip fertigation system, solving both issues at the same time. Another possible way in which this challenge can be overcome is by using robotic tractors. One of the interviewees, namely Huijts suggested that autonomously operating tractors with light, small implements might be a way forward, without losing out on efficiency.

Summary

So, to conclude, there are a number of technological limitations that should be taken into consideration when converting to intercropping as well as technological hurdles that will have to be overcome depending on the intercropping system, but overall, one can convert from a conventional way of farming to certain types of intercropping without too much difficulty.

RQ6 – What are the current socio-economic bottlenecks for implementing intercropping in the Netherlands?

We've identified three main themes that were shared among the interviewees. First, the interviews uncovered policy and research related issues. Secondly, economic stability and security was a point of concern. Lastly, some interviewees observed or experienced social or societal barriers for the implementation of intercropping. Each theme was worked out separately.

Policy/Research

One of the main concerns from researchers as well as farmers was the lack of a long-term vision on agriculture by policy makers. The change in government every 4 years can bring along different viewpoints on (the future of) agriculture. An example is the change in government in November 2023 and the shifting view upon nitrogen legislation (NOS, 2024). Interviewees mentioned that farmers were willing to adopt new cultivation systems, if there was a clear, stable vision that their investment would yield returns for them long-term. Huijts based a substantial amount of his turnover on economic compensation for ecosystem services. Whilst this provided a more stable cashflow than the revenue from agricultural goods, it still relied on stable policies. The idea that a change in government could potentially bring a change in agricultural legislation was not shared by all farmers. Tigchelaar, J. Jurrius and A. Jurrius expected that the future could bring stricter legislation surrounding fertiliser and chemical crop protection. This could then steer to more mixed or strip cropping systems. Promoting this change would require supportive policies.

Secondly, farmers and researchers both mentioned that farmers feel as if there is too little space and freedom to experiment, due to policies and competitive markets. Furthermore, more representative and useful results may be generated when researchers would help farmers study their mixtures. This may help in generating. Then researchers and farmers could communicate to manufacturers what machinery should be designed to accommodate those new systems. They both agreed that there should be room in policies to be able to do such experiments in order to advance.

Communication

All parties agreed that there was a lack of communication between farmers, researchers and policy makers. Dong pointed at the governmental demand for lower nitrogen emissions by farmers through reduced fertiliser use. According to them, the government lacked the consideration that lower nitrogen input would also result in a lower system output, if farmers would stick to monoculture. They also stressed that researchers sometimes miss the connection with practice due to the lack of communication between researchers and farmers. Cobben stated the benefits of having trees in the landscape. But the implementation is hindered by outdated policies, the lack of knowledge by policy makers, and the lack of communication with farmers. Which in turn is preventing a more diverse landscape, especially in the northern provinces. The three parties should work together, but also communicate to each other. According to Wang, by enhanced knowledge exchange between researchers and farmers, researchers could play a mediating role between the farmers and the government.

It is at the point of information between researchers and farmers where opposing views were encountered. On the one hand, van Apeldoorn stated that there was enough information available about intercropping. On the other hand, farmers stated that there was limited information accessible. Besides, A. Jurrius noted that not all available research is helpful or that the evidence isn't convincing enough. He now has to do his own research into intercropping, which demands time and financial investments. J. Jurrius also realised that intercropping is a fairly new system and therefore information in magazines is not that extensive yet. Furthermore, Huijts mentioned that available research is not always applicable to his soil. He therefore has to look into French, Belgian or German literature to get information. Researchers and policy makers could support farmers by creating a common platform where papers about intercropping and advances in agriculture in general, are compiled into understandable information, preferable in, or translated to, Dutch.

Administration

Lastly, administrative challenges were also brought up by Huijts and J. Jurrius and acknowledged by Cobben from RVO. Each strip must be individually administered, which is a timely process and becomes more tedious, the smaller the strips get. Moreover, new RVO regulations for a parcel demand a resting crop for one year after 3 years of cultivation. This is less of a problem in well defined, GPS outlined, parcels. But a system where the areas of the strips change every season, is prone to administrative errors, and therefore fines. An option would then be for RVO to demand that a certain percentage of arable land should be used for a resting crop in the rotation. Working in set-out parcels would be preferable however, stressing the benefit of GPS-based agriculture. Eventually, RVO could streamline administrative processes by combining the GPS-data with the crop on a given parcel, suggested by Huijts. The decrease in manual administration ties in with the statement from Van Apeldoorn that 'time is the biggest problem, not money'. A last interesting view from J. Jurrius was that the complex RVO legislation was a result of the farmers' lobby, which demanded many exceptions. He said that RVO also prefers less complex legislation. Cobben from RVO confirmed this view.

Economical Aspects

Researchers and farmers found common ground on monetary issues. While money in itself was not necessarily stated as being the problem, the perceived risks that may come along with a change in cultivation system were. According to Van Apeldoorn and Cobben, farmers are entrepreneurs, generally looking for short-term profits rather than beneficial effects over time. This relatively shorter-term view may enhance the perceived risks and hesitation of farmers towards investment.

Investments & Expenses

A major point of concern shared among farmers were irrigation and labour. Strip cropping for example, often requires a different irrigation technique than a monoculture. According to Huijts, investing in an irrigation system catering strip cropping may require about €100.000. J. Jurrius reinforced this view saying that on, for example, sandy soil types, you would need high revenue crop types to make a drip irrigation system viable. This was not the case on his farm. Such a system could work, but more so on clay soils. On top of that, labour costs or the investment in new machinery was mentioned by most farmers as a challenge, especially for larger areas. This view is backed by Raza et al. (2023) and Huss et al. (2022). Huijts proposed using robotics in the future, which are more efficient, save time for the farmer, and decreases manual labour costs. Tigchelaar also mentioned being interested in using robotics for weeding, although not specific to intercropping, he stated that it would save him time. Once again reiterating the statement from Van Apeldoorn that time is an important limiting factor. For the transition from monoculture to a more diverse cropping system, a strip cropping system with wider strips, accommodating current machinery, may be a viable first step (Juventia et al., 2022).

Subsidies & Risk aversion

The view on subsidies differed between researchers, the policy maker and farmers, but also amongst farmers themselves. According to Van Apeldoorn and Cobben, financial incentives could support farmers in the transition to an intercropping system, but farmers should not be dependent on subsidies to have a viable business. It would be better if intercropping products had higher prices instead, as will be discussed later. Huijts took a different approach and saw the subsidies more as financial compensation for his care for the local ecosystem. He was convinced that including more diversity was better for his land and made ecosystem services an integral part of his agricultural system. This resulted in a slight decrease in revenue from yield, but a more stable turnover.

Farmers in general agreed that subsidies could be used during the transition to an intercropping system but should not be necessary afterwards to make this new system economically viable. But J. Jurrius even preferred continuing doing monoculture and stated that financial support should only be used for biodiversity-promoting incentives, such as flower strips bordering fields. This farmer also touched upon another issue that subsidies appreciate land value, resulting in large landowners demanding more tenancy. Therefore, subsidy funds go indirectly to third parties, instead of the intended recipients. The interview with Cobben revealed the same opinion. A similar line of reasoning was encountered by Tigchelaar, talking about specialised machinery for intercropping.

In contrast to other farmers, Huijts saw 21m width strip cropping as less risky compared to monoculture. Risk reduction by crop diversification is supported by (Mousavi & Eskandari, 2011). According to Tigchelaar, an intercropping system may be more input efficient but yield volume may be lower depending on crop selection. Lower volume can, in case of potatoes for example, be seen as economically more challenging. Risk of yield loss due to interspecific competition can be reduced by proper crop selection and sowing strategy (Huss et al., 2022; Maitra et al., 2021).

Path-dependency might also play a role. The whole agricultural system is now set up for large scale monoculture, buying in bulk and large machines. Past investments may hinder farmers from taking risks and adopting a new system. The lack of backup funds, space and time to experiment, combined with this path-dependency might also be a hurdle for farmers according to a researcher.

The use of biodiversity

A striking difference was observed in the vision about biodiversity. Most farmers prefer economic stability and efficiency over biodiversity and therefore see biodiversity more as a tool to decrease fertiliser or pesticide use. This was acknowledged by Van der Werf. While Huijts, Cobben, Van Apeldoorn saw biodiversity as the goal, supported by financial compensation for ecosystem services. In their view, more biodiversity results in a healthier and more sustainable ecosystem, while yield stability and/or increase are secondary economic benefits. Introducing nature back into the system may sound beneficial for biodiversity, but it raised another major challenge.

Market & post-harvest challenges

According to Van Apeldoorn, system biodiversity leads to crop diversity, and that is undesirable for retailers. There was consensus among researchers and farmers that there currently is no market for intercrops. There are 2 sides of this problem. On the one hand, supermarkets prefer uniformity but intercropping, with lower nitrogen input for example, may produce less uniform products. On the other hand, products harvested from mixed intercropping fields would need post-harvest separation. This requires an extra step in the processing chain, increasing labour and cost.

Researchers and farmers agreed that the brand image for intercropping products should be enhanced to create a market for them. Prices currently support monocropping products which may slow intercropping adoption (Manevska-Tasevska et al., 2024). Farmers, researchers as well as the policy maker also noted that the infrastructure for short-chain markets needs improvement. Farmers prefer local markets for their (intercropped, diverse) products. Besides, Dong hypothesised that consumers might be more willing to pay a higher price for locally produced, sustainably grown foods. Research by Aschemann-Witzel & Zielke (2017) and S. Li & Kallas (2021) has shown the willingness of consumers to pay more for organic foods. Therefore, with a strategic brand image creation for intercrops, farmers may get higher revenues in the future. This might subsequently incentivise farmers to implement intercropping. Also, by removing intermediaries, farmers target enhanced revenue. While being responsible for the chain and the quality of the product is a risk, the reward is at least worth considering according to Huijts.

Social Aspects

On the positive side, Van Apeldoorn argued that society benefits from strip cropping. He said that farmers and citizens were more excited to see intercropping fields and found them aesthetically pleasing. He hypothesised that the connection between citizens and farmers could improve through this shared appreciation. The lack of connection between farmers and citizens, and among farmers, was also brought up by multiple farmers themselves.

Van Apeldoorn also stated that intercropping and conventional farmers question each other's results. From a research group he noticed that local farmers, who know each other's fields, were more likely to share problems, compared to a diverse group. There also appears to be a form of peer-pressure among farmers to stick to conventional methods. Paraphrased, Van Appeldoorn anecdotally argued that farmers may say: 'if I switch to intercropping, my neighbours will say, oh, am I not doing it right? And by doing it, you prove that we are not doing it right.'

The lack of communication between farmers was noticed from the interviews, as nearly all mentioned that they do not speak to a lot of other farmers. The urge for knowledge exchange and cooperation to advance was affirmed by nearly all participants. Multiple farmers acknowledged hesitancy themselves or from other farmers to implement an intercropping system due to added system complexity and yield uncertainty. These barriers were also mentioned by (Huss et al., 2022). And as proposed, this hesitancy could be an effect of path-dependency. On a deeper level, it may also be traced back to generational habits and the successes of current practices.

Summary

There are a few key take-aways regarding the socio-economic bottlenecks for the implementation of intercropping. Farmers and researchers see the lack of long-term agricultural policy as a hurdle, together with poor communication between farmers, researchers, and policy makers. Economically, high investment costs for irrigation and/or machinery, and the absence of a market for intercrop products are barriers to the adoption of an intercropping system. On the social side, there is perceived peer pressure from conventional farmers against change. Additionally, limited communication among farmers, concerns about the perceived complexity (both system and administration), and uncertainty of yields add to the hesitancy to transition.

Additional findings

Moreover, our research also led to some findings which are not covered in one of the research questions. These will be discussed below.

First off, it became clear from interviews that most farmers are willing to think about transitioning their practices, especially organic farmers. As they already transitioned in the past to a non-standard farming system (organic compared to conventional), this shows they are more flexible and willing to change. Moreover, switching to an intercropping system is in line with some of the organic farming principles. As organic farming relies on no chemical inputs (fertiliser, pesticides), and intercropping reduces the need for these, intercropping makes organic farming more robust.

However, the reason for switching to an intercropping system differs per farmer. Some are interested in the more robust system (less diseases, biological control against pest species), others are interested in higher yield and in turn higher profits, and finally some farmers would like a more efficient system. This also leads to different expectations of what a cropping system should provide: e.g. for those interested in an efficient system, it should be easy and time efficient.

Table of Agreements and Visual Compendium

To synthesise the information gathered from our literature research, complemented with insights gleamed from the performed interviews, we created a *Table of agreements* (Table 1) as well as a *visual compendium* (Figure 4). These aim to provide an overview of the findings as well as highlight the links between the intricate network behind intercropping and the transition towards a more diverse cropland.

Table 1 shows an overview how the different interviewees perceive aspects of intercropping and what they agree and disagree on, and what the current bottlenecks are according to them. Further information on these points can be found in our report, as this table only summarizes these views.

Figure 4 displays the network which is involved with the transition to a diverse agricultural landscape by means of intercropping. We mapped out five distinct aspects of this transition which cover the crop combinations, benefits (farmers' and ecological), and bottlenecks (Society and Technology) of intercropping. These five aspects were further subdivided into their fundamental elements (boxes) which result from a complex web of interacting traits, mechanisms, and agents (ovals). These have increasing (orange arrow), decreasing (blue arrow), or merely relational connections (dotted line) with each other. As a whole, the visual compendium characterizes the complexity of the transition to a diverse cropland, even with only intercropping being examined. The linkages highlight the enormous scale of this issue and illustrate that a single change somewhere can cause cascading and multifaceted impacts in the bigger picture.

Table 1: An overview of where the statements of our interviewees align or diverge with each other, as well as bottlenecks they mentioned. These have been separated based on our classification on whether these are major or minor issues on the topic of re-diversifying the Dutch agricultural landscape.

	Major	Minor
Agreements	- All interviewees agree that intercropping needs to be efficient to work, however disagreements were found as to what specifically needs to be efficient. - Interviewed farmers do not see mechanisation as a huge challenge but acknowledge increasing difficulty with narrow strips. - There is no proper market for intercropping products (i.e. Mixed harvest, variable product sizes). - Farmers need more long-term stability to transition, and more freedom to experiment. - Subsidies should be for experiments and transitions. The business should not rely on them. - Wider crop strips are easier to implement but lack benefits from plant complementarity. - Intercropping increases resilience to pests and diseases, mainly through physical barriers. - Not everyone is willing to transition, intercropping is a more sensitive topic for conventional farmers, less so for organic farmers. However, with the right rewards (yield, money, efficiency, resilience) most are willing to transition.	- Among researchers, mechanisation is seen as a problem. - Chemicals restrictions will continue and ramp up. Alternatives will be needed. - Global positioning services (GPS) is invaluable for designing intercropping implementations. - Breeding for intercropping is under researched. - Culture / Habit / Traditions often influence system over logic.
Disagreements	- Interviewees did not have consistent definitions of intercropping. What intercropping meant to them was heavily dependent on their type of involvement with the topic. - There are diverging views on availability of knowledge, some researchers think there is plenty, some think there is not enough. Interviewed farmers reported differing levels of access to information. - The expectations of intercropping, i.e. what benefits were expected from transitioning, differed between interviewees. - Whether or not perfect combinations exist. (Agreement on the existence of numerous bad combinations). - Whether or not biodiversity should be a goal or a tool. - The path financial incentives should take to get to the farmer (i.e. subsidy, compensation, insurance or fine?).	- The degree of importance of capital to the farmer was not universally agreed upon. Researchers tended to think capital was quite important, whereas many farmers did not consider it to be a major issue.
Bottlenecks	- No long-term governmental vision on agricultural policies. - No centralised location for information, the mismatch between information existence and accessibility. - Lacking market for intercrop products (As well as no brand image). - Lacking communication between farmers, researchers, and policy makers. - Lacking infrastructure for short supply chains (most infrastructure is geared towards large-scale, globalised operations). - Lacking freedom for farmers to experiment (due to time constraints, regulation, profit margins/risk). - The amount of paperwork currently necessary to deal with intercropping setups (i.e. Landbouw register, Kadaster, RVO). - No one-size-fits-all solution. The added complexity when local conditions need to be considered.	- Specialised machinery for certain intercropping strip widths. - Lacking breeding programs specifically for intercropping.

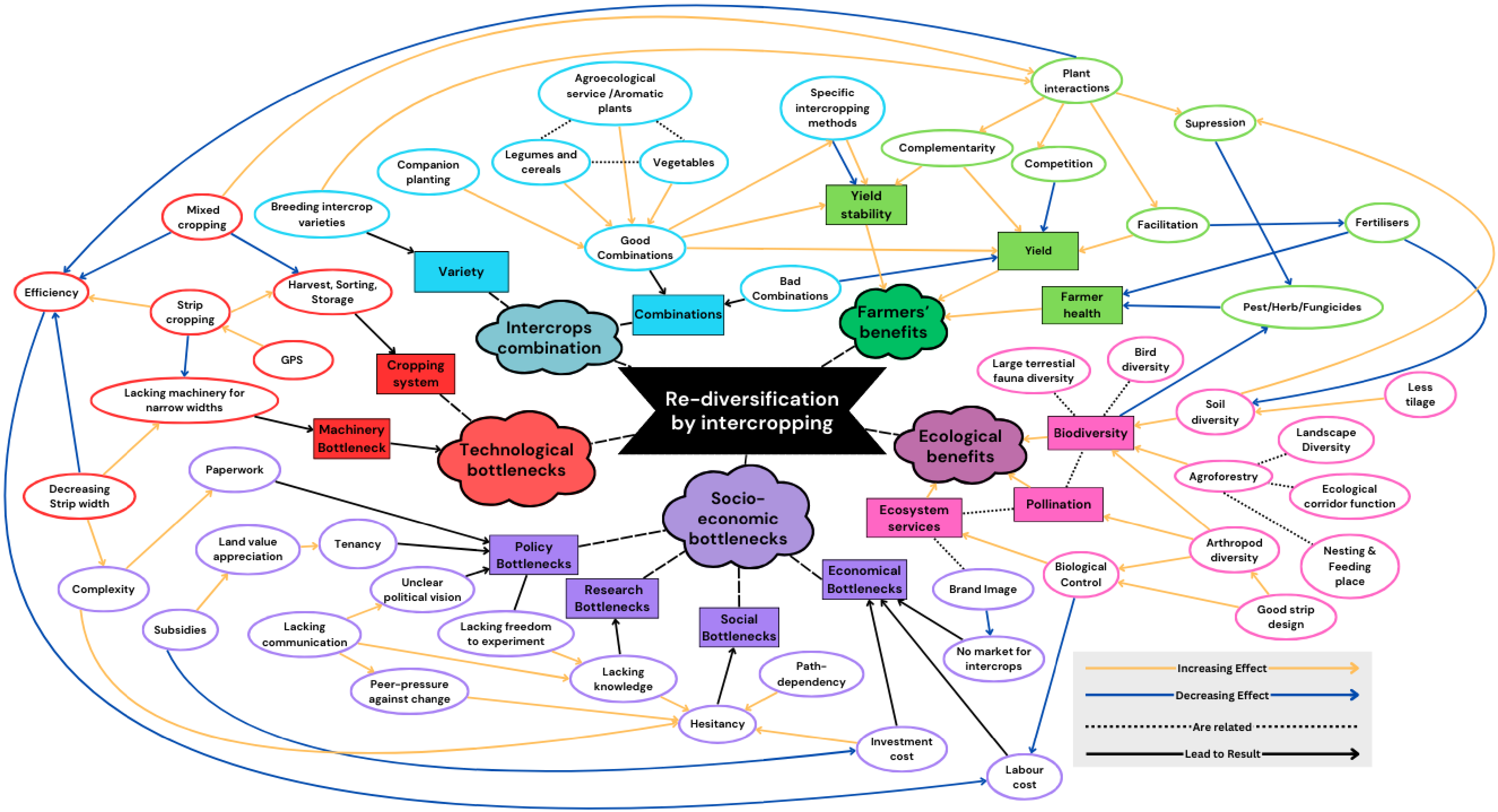

Figure 4: The Visual Compendium aims to visualise the network of intertwined processes and actors involved in the re-diversification of the agricultural landscape by means of intercropping. Orange arrows indicate positive feedback (increasing effect) between elements, whereas blue arrows represent negative feedback (decreasing effect). Elements always lead to a result (black arrow), and dotted lines represent relational connections.

Recommendations

This next section will shortly summarise our most important findings and give advice on what actions could be taken next.

- *Agree on using the correct terminology for intercropping, and its constituents, between all parties before having a discussion.*

When analysing our interviews, it became clear that each interviewee used the broad term of intercropping instead of the terminology for the underlying system. This is inconvenient for comparisons, both in discussions, and literature. Therefore, it is important that all parties use the correct terminology, so no confusion arises.

- *Make a good cropping design for well-functioning ecosystem services.*

Intercropping influences the following ecosystem services: pollination and biological crop control. A diverse crop mix, with a small distance from other flowering crops, attracts a variety of pollinators. This increases the rate, stability and likelihood of pollination. Biological control is dependent on crop selection. Crops which host predatory species, should be placed next to crops vulnerable to pests.

- *Implement elements of agroforestry for improved biodiversity.*

Besides pollinators, other animals also benefit from intercropping. Meadow birds prefer the open strip cropping fields and use hedges around the farmland to nest and feed. Forest birds use the hedges and other agroforestry elements as ecological corridors to nature areas. Arthropods and large fauna, such as hedgehogs, perform well in agroforestry fields. Therefore, implementing some elements of agroforestry, such as planting hedges, could improve biodiversity. Creating a small (food) forest, would improve biodiversity even more.

- *Minimise tillage and leave plant residues on fields to improve soil biodiversity and health.*

With less tillage and more organic matter, the soil biodiversity increases. Therefore, farmers should plough as little as possible and leave some plant material behind on the fields. This would also increase earthworm presence, which in turn would improve the soil by increasing water infiltration and soil porosity. Further study on below-ground processes and mycorrhiza is recommended.

- *A viable first step is to switch to a wide strip strip-cropping system, with subsidies only for the transition.*

Transitioning towards intercropping might be a big change for farmers. However, implementing wide strip strip-cropping, or mixed cropping on some fields, would be beneficial to biodiversity. Bird abundance and diversity both increase at 12 m wide strips. Moreover, most current machines are suitable to work on 12 m wide strips, decreasing the need to invest in new machinery. At this width, birds increase both their abundance and diversity.

A mixed cropping field of legume and wheat would reduce the input need of fertiliser, benefitting the farmer both in time and expenses. During the transition phase, subsidies could be used to support farmers. However, subsidies should only be used during the transition phase. The system should be economically viable independent of subsidies.

- *Shorten market chains and (re)construct small-scale processing facilities.*

There is currently (almost) no market for intercropping products. Crops are most commonly sold to large supply chains, with less options for local distribution. Shorter market chains and small-scale processing facilities should be (re)constructed. This would simplify selling intercropping products on a local level. Moreover, by increasing vertical integration, farmers may be more responsible for the chain and quality of their product. While this brings a risk, the reward is at least worth considering.

- *Design machinery that is suitable for strips smaller than 3 meters wide.*

As mentioned before, smaller strips (3 meters or less) provide more benefits, but decrease the ability of mechanisation. Therefore, there should be more machines designed that can operate on strips narrower than 3 metres.

- *Provide information about intercropping for society and farmers, with specific information tailored towards organic farmers.*

There is not much accessible information about intercropping available for society and farmers. The information available, is not easily understandable, and often not in Dutch. To improve general awareness on intercropping, providing easily accessible and comprehensible information is necessary.

As mainly organic farmers are interested in transitioning their farming practices, it is wise to provide information about intercropping specifically to them. This can include that intercropping is in line with the organic principle of chemical-free crop cultivation. Additionally, it will make their systems more robust to pests. Finally, as every farmer has their own reason for considering an intercropping system, it is important to discuss all the facets of intercropping.

- *Perform further research on intercropping combinations, intercropping specific crop breeding and design.*

The three most common intercropping combinations are vegetable-vegetable, legume-cereal, and edible crops-agroecological/aromatic plants. We were unable to identify optimal crop pairings, however, there are bad combinations that will sacrifice one crop due to interspecific competition. A form of intercropping, companion planting, is a "push-pull" system. While the plants in this system are not necessarily meant for consumption, their mechanisms can act as a reference for future research on intercropping. Crops currently used for intercropping research are optimised for monoculture. Therefore, more research on varieties tailored towards intercropping, and subsequent breeding, is recommended.

Theoretically, a lot of combinations of crops could help mitigate certain environmental pressures, but in practice, only a few are known to work. For example, reshaping/improving soil via crop mixes is already a tool known to intercropping and conventional farmers in the Netherlands. Intercropping has a lot of benefits in low input cropping systems such as organic farming, or low N-application conventional systems. Legumes and other plants, as white lupin, have N-fixing and P-mobilising capabilities, respectively. This reduces the need for artificial N and P fertilisers. Besides, crop mixtures could increase the water retention capacity of the soil by increasing SOM production. This would especially be useful on sandy soils, or soils with a very low groundwater table. Intercropping with species that have a potential for supplying water via hydraulic lift is helpful in dry environments, but this is only possible up to around 10 m for most trees, and 1 m for grasses and herbs (Y. Fan et al., 2017) .

Choose neighbouring plants which supplement each other. A good pairing maximises plant trait complementarity, such as optimal niche space, facilitation of resource sharing and suppression of weeds. The benefits of intercropping increase with higher plant interactions, but this decreases the ability of mechanisation. Therefore, a good balance of these two factors should be kept in mind. Moreover, a better understanding of complex plant interactions can help with the intercropping design, as this is currently understudied.

- *Take home message.*

Intercropping can give many benefits, with the right design. To make more intercropping more feasible for farmers, some economic change is necessary in the market and supply chain. Additional research should be performed on plant breeding and complex plant relationships tailored towards intercropping.

Final conclusions

Our main research question is: **What are the current benefits & limitations of different intercropping mixtures in relation to local environments?**

Currently, in intercropping a standard mixture consists of legumes and cereals. This combination is common since it reduces pests and disease pressure and increases nitrogen fixation which in turn reduces the need for artificial N fertilisers. The farmers are still using monoculture varieties in their systems, as there are no specific crop varieties for intercropping. There are all kinds of resource competitions in intercropping mixtures, so special varieties with higher complementarity in intercropping systems are necessary to be researched. Overall, technical limitations were not found to be the biggest part hindering the transition towards a more diverse agricultural landscape, the most important parts to tackle are the societal benefits, limitations and bottlenecks. Society needs to be the driver of change.

An important way to enact this change is to create awareness by the general public on the value of biodiversity, and intercropping. Creating a brand image, ideally at a European level, for "diversity crops" could generate a market for intercropped crops. In general, it is important to be more activistic as researchers and actively reach out to the government, the agricultural sector, food industry, consumers and other stakeholders to stir up the dialogue on diversification of the agricultural landscape and its value for biodiversity and society.

References

Aizen, M. A., Aguiar, S., Biesmeijer, J. C., Garibaldi, L. A., Inouye, D. W., Jung, C., Martins, D. J., Medel, R., Morales, C. L., Ngo, H., Pauw, A., Paxton, R. J., Sáez, A., & Seymour, C. L. (2019). Global agricultural productivity is threatened by increasing pollinator dependence without a parallel increase in crop diversification. *Global Change Biology*, *25*(10), 3516–3527. https://doi.org/https://doi.org/10.1111/gcb.14736

Alarcón-Segura, V., Grass, I., Breustedt, G., Rohlfs, M., & Tscharntke, T. (2022). Strip intercropping of wheat and oilseed rape enhances biodiversity and biological pest control in a conventionally managed farm scenario. *Journal of Applied Ecology*, *59*(6), 1513–1523. https://doi.org/https://doi.org/10.1111/1365-2664.14161

Arheimer, B., Torstensson, G., & Wittgren, H. B. (2004). Landscape planning to reduce coastal eutrophication: agricultural practices and constructed wetlands. *Landscape and Urban Planning*, *67*(1), 205–215. https://doi.org/https://doi.org/10.1016/S0169-2046(03)00040-9

Aschemann-Witzel, J., & Zielke, S. (2017). Can't Buy Me Green? A Review of Consumer Perceptions of and Behavior Toward the Price of Organic Food. *Journal of Consumer Affairs*, *51*(1), 211–251. https://doi.org/https://doi.org/10.1111/joca.12092

A.V., V. B., Weedon, O. D., & Finckh, M. R. (2019). Exploring the differences between organic and conventional breeding in early vigour traits of winter wheat. *European Journal of Agronomy*, *105*, 86–95. https://doi.org/https://doi.org/10.1016/j.eja.2019.01.008

Awal, M. A., Koshi, H., & Ikeda, T. (2006). Radiation interception and use by maize/peanut intercrop canopy. *Agricultural and Forest Meteorology*, *139*(1), 74–83. https://doi.org/https://doi.org/10.1016/j.agrformet.2006.06.001

Batáry, P., Kovács-Hostyánszki, A., Fischer, C., Tscharntke, T., & Holzschuh, A. (2012). Contrasting effect of isolation of hedges from forests on farmland vs. woodland birds. *Community Ecology*, *13*(2), 155–161. https://doi.org/https://doi.org/10.1556/comec.13.2012.2.4

Beniston, M., Stephenson, D. B., Christensen, O. B., Ferro, C. A. T., Frei, C., Goyette, S., Halsnaes, K., Holt, T., Jylhä, K., Koffi, B., Palutikof, J., Schöll, R., Semmler, T., & Woth, K. (2007). Future extreme events in European climate: an exploration of regional climate model projections. *Climatic Change*, *81*(1), 71–95. https://doi.org/10.1007/s10584-006-9226-z

Bennett, E. M., Peterson, G. D., & Gordon, L. J. (2009). Understanding relationships among multiple ecosystem services. *Ecology Letters*, *12*(12), 1394–1404. https://doi.org/https://doi.org/10.1111/j.1461-0248.2009.01387.x

Bieleman, J. (2010). *Five centuries of farming: a short history of Dutch agriculture 1500-2000* (Vol. 8). BRILL.

Biswas Chowdhury, R., & Zhang, X. (2021). Phosphorus use efficiency in agricultural systems: A comprehensive assessment through the review of national scale substance flow analyses. *Ecological Indicators*, *121*, 107172. https://doi.org/https://doi.org/10.1016/j.ecolind.2020.107172

Boeckx, P., & Van Cleemput, O. (2001). Estimates of N2O and CH4 fluxes from agricultural lands in various regions in Europe. *Nutrient Cycling in Agroecosystems*, *60*(1), 35–47. https://doi.org/10.1023/A:1012604032377

Bos, J. F. F. P., Haan, J. de, Sukkel, W., & Schils, R. L. M. (2014). Energy use and greenhouse gas emissions in organic and conventional farming systems in the Netherlands. *NJAS - Wageningen Journal of Life Sciences*, *68*, 61–70. https://doi.org/https://doi.org/10.1016/j.njas.2013.12.003

Boudsocq, S., Niboyet, A., Lata, J. C., Raynaud, X., Loeuille, N., Mathieu, J., Blouin, M., Abbadie, L., & Barot, S. (2012). Plant Preference for Ammonium versus Nitrate: A Neglected Determinant of Ecosystem Functioning? *The American Naturalist*, *180*(1), 60–69. https://doi.org/10.1086/665997

Bourke, P. M., Evers, J. B., Bijma, P., van Apeldoorn, D. F., Smulders, M. J. M., Kuyper, T. W., Mommer, L., & Bonnema, G. (2021). Breeding beyond monoculture: Putting the "intercrop" into crops. *Frontiers in Plant Science*, *12*, 734167.

Breidenbach, J. (2017). *Voedselbossen van belang voor biodiversiteit*. https://netwerkvoedselbosbouw.nl/wp-content/uploads/2019/03/DLN-Breidenbach-e.a.-Voedselbossen-van-belang-voor-biodiversiteit-2017.pdf

Britto, D. T., & Kronzucker, H. J. (2013). Ecological significance and complexity of N-source preference in plants. *Annals of Botany*, *112*(6), 957–963. https://doi.org/10.1093/aob/mct157

Bybee-Finley, K. A., & Ryan, M. R. (2018). Advancing intercropping research and practices in industrialized agricultural landscapes. *Agriculture*, *8*(6), 80.

Cleophas, F., Isidore, F., Musta, B., Ali, B. N. M., Mahali, M., Zahari, N. Z., & Bidin, K. (2022). Effect of soil physical properties on soil infiltration rates. *Journal of Physics: Conference Series*, *2314*(1), 012020.

Cong, W.-F., Hoffland, E., Li, L., Six, J., Sun, J.-H., Bao, X.-G., Zhang, F.-S., & Van Der Werf, W. (2015). Intercropping enhances soil carbon and nitrogen. *Global Change Biology*, *21*(4), 1715–1726. https://doi.org/https://doi.org/10.1111/gcb.12738

Crittenden, S. J., Huerta, E., de Goede, R. G. M., & Pulleman, M. M. (2015). Earthworm assemblages as affected by field margin strips and tillage intensity: An on-farm approach. *European Journal of Soil Biology*, *66*, 49–56. https://doi.org/https://doi.org/10.1016/j.ejsobi.2014.11.007

Cu, S. T. T., Hutson, J., & Schuller, K. A. (2005). Mixed culture of wheat (Triticum aestivum L.) with white lupin (Lupinus albus L.) improves the growth and phosphorus nutrition of the wheat. *Plant and Soil*, *272*(1), 143–151. https://doi.org/10.1007/s11104-004-4336-8

Dai, C.-C., Chen, Y., Wang, X.-X., & Li, P.-D. (2013). Effects of intercropping of peanut with the medicinal plant Atractylodes lancea on soil microecology and peanut yield in subtropical China. *Agroforestry Systems*, *87*(2), 417–426. https://doi.org/10.1007/s10457-012-9563-z

Dankers, R., & Feyen, L. (2008). Climate change impact on flood hazard in Europe: An assessment based on high-resolution climate simulations. *Journal of Geophysical Research: Atmospheres*, *113*(D19). https://doi.org/https://doi.org/10.1029/2007JD009719

de Medeiros, E. V., Notaro, K. de A., de Barros, J. A., Duda, G. P., Moraes, M. de C. H. dos S., Ambrósio, M. M. de Q., Negreiros, A. M. P., & Sales Júnior, R. (2019). Soils from intercropped fields have a higher capacity to suppress black root rot in cassava, caused by Scytalidium lignicola. *Journal of Phytopathology*, *167*(4), 209–217. https://doi.org/https://doi.org/10.1111/jph.12788

Dijk, R. (2019). *How do Dutch farmers decide to adopt crop diversification practices? The role of knowledge acquisition* [WUR]. https://edepot.wur.nl/507795

Ecosystems United. (2024, October 8). *an introduction to intercroppin*. https://ecosystemsunited.com/2017/01/24/an-introduction-to-intercropping/

Ehrmann, J., & Ritz, K. (2014). Plant: soil interactions in temperate multi-cropping production systems. *Plant and Soil*, *376*(1), 1–29. https://doi.org/10.1007/s11104-013-1921-8

El-Hamawi, M. H., Youssef, M. M. A., & Zawam, H. S. (2004). Management of Meloidogyne incognita, the root-knot nematode, on soybean as affected by marigold and sea ambrosia (damsisa) plants. *Journal of Pest Science*, *77*(2), 95–98. https://doi.org/10.1007/s10340-003-0034-1

Faget, M., Nagel, K. A., Walter, A., Herrera, J. M., Jahnke, S., Schurr, U., & Temperton, V. M. (2013). Root–root interactions: extending our perspective to be more inclusive of the range of theories in ecology and agriculture using in-vivo analyses. *Annals of Botany*, *112*(2), 253–266. https://doi.org/10.1093/aob/mcs296

Fan, F., Zhang, F., Song, Y., Sun, J., Bao, X., Guo, T., & Li, L. (2006). Nitrogen Fixation of Faba Bean (Vicia faba L.) Interacting with a Non-legume in Two Contrasting Intercropping Systems. *Plant and Soil*, *283*(1), 275–286. https://doi.org/10.1007/s11104-006-0019-y

Fan, Y., Miguez-Macho, G., Jobbágy, E. G., Jackson, R. B., & Otero-Casal, C. (2017). Hydrologic regulation of plant rooting depth. *Proceedings of the National Academy of Sciences*, *114*(40), 10572–10577. https://doi.org/10.1073/pnas.1712381114

Fares, M., & Mamine, F. (2023). Relative Importance of Barriers and Levers to Intercropping Systems Adoption: A Comparison of Farms and Co-Operatives. *Sustainability*, *15*(8), 6652.

Frankow-Lindberg, B. E., & Dahlin, A. S. (2013). N2 fixation, N transfer, and yield in grassland communities including a deep-rooted legume or non-legume species. *Plant and Soil*, *370*(1), 567–581. https://doi.org/10.1007/s11104-013-1650-z

Fujita, H., Aoki, S., & Kawaguchi, M. (2014). Evolutionary Dynamics of Nitrogen Fixation in the Legume–Rhizobia Symbiosis. *PLOS ONE*, *9*(4), e93670-. https://doi.org/10.1371/journal.pone.0093670

Furtak, K., & Wolińska, A. (2023). The impact of extreme weather events as a consequence of climate change on the soil moisture and on the quality of the soil environment and agriculture – A review. *CATENA*, *231*, 107378. https://doi.org/https://doi.org/10.1016/j.catena.2023.107378

Gallai, N., Salles, J.-M., Settele, J., & Vaissière, B. E. (2009). Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics*, *68*(3), 810–821. https://doi.org/https://doi.org/10.1016/j.ecolecon.2008.06.014

Gebru, H. (2015). A review on the comparative advantages of intercropping to mono-cropping system. *Journal of Biology, Agriculture and Healthcare*, *5*(9), 1–13.

Georgi, N. J., & Zafiriadis, K. (2006). The impact of park trees on microclimate in urban areas. *Urban Ecosystems*, *9*, 195–209.

Giles, C. D., Richardson, A. E., Cade-Menun, B. J., Mezeli, M. M., Brown, L. K., Menezes-Blackburn, D., Darch, T., Blackwell, M. S. A., Shand, C. A., Stutter, M. I., Wendler, R., Cooper, P., Lumsdon, D. G., Wearing, C., Zhang, H., Haygarth, P. M., & George, T. S. (2018). Phosphorus acquisition by citrate- and phytase-exuding plant mixtures depends on soil phosphorus availability and root intermingling. *Physiologia Plantarum*, *163*(3), 356–371. https://doi.org/https://doi.org/10.1111/ppl.12718

Godijn, N., Klaassen, R., & Ottens, H. J. (2022). *Broedende Veldleeuweriken en strokenteelt in Zeeland in 2021-2022*.

Gou, F., van Ittersum, M. K., Simon, E., Leffelaar, P. A., van der Putten, P. E. L., Zhang, L., & van der Werf, W. (2017). Intercropping wheat and maize increases total radiation interception and wheat RUE but lowers maize RUE. *European Journal of Agronomy*, *84*, 125–139. https://doi.org/https://doi.org/10.1016/j.eja.2016.10.014

Hansen, G., & Stone, D. (2016). Assessing the observed impact of anthropogenic climate change. *Nature Climate Change*, *6*(5), 532–537. https://doi.org/10.1038/nclimate2896

Harwood, J. (2024). The forgotten history of intercropping. *PLANTS, PEOPLE, PLANET*, *6*(5), 1121–1128. https://doi.org/https://doi.org/10.1002/ppp3.10502

Hassan, A., Dresbøll, D. B., Rasmussen, C. R., Lyhne-Kjærbye, A., Nicolaisen, M. H., Stokholm, M. S., Lund, O. S., & Thorup-Kristensen, K. (2021). Root distribution in intercropping systems – a comparison of DNA based methods and visual distinction of roots. *Archives of Agronomy and Soil Science*, *67*(1), 15–28. https://doi.org/10.1080/03650340.2019.1675872

Homulle, Z., George, T. S., & Karley, A. J. (2022a). Root traits with team benefits: understanding belowground interactions in intercropping systems. *Plant and Soil*, *471*(1), 1–26. https://doi.org/10.1007/s11104-021-05165-8

Homulle, Z., George, T. S., & Karley, A. J. (2022b). Root traits with team benefits: understanding belowground interactions in intercropping systems. *Plant and Soil*, *471*(1), 1–26. https://doi.org/10.1007/s11104-021-05165-8

Hondebrink, M., Barbry, J., Himanen, S., Lakkenborg, H., Lepse, L., Trinchera, A., & Koopmans, C. J. (2019). *Overview of farmers expected benefits of diversification. Report on national stakeholder involvement.*

Hooks, C. R. R., Wang, K.-H., Ploeg, A., & McSorley, R. (2010). Using marigold (Tagetes spp.) as a cover crop to protect crops from plant-parasitic nematodes. *Applied Soil Ecology*, *46*(3), 307–320. https://doi.org/https://doi.org/10.1016/j.apsoil.2010.09.005

Hu, H.-Y., Li, H., Hao, M.-M., Ren, Y.-N., Zhang, M.-K., Liu, R.-Y., Zhang, Y., Li, G., Chen, J.-S., Ning, T.-Y., & Kuzyakov, Y. (2021). Nitrogen fixation and crop productivity enhancements co-driven by intercrop root exudates and key rhizosphere bacteria. *Journal of Applied Ecology*, *58*(10), 2243–2255. https://doi.org/https://doi.org/10.1111/1365-2664.13964

Hufnagel, J., Reckling, M., & Ewert, F. (2020). Diverse approaches to crop diversification in agricultural research. A review. *Agronomy for Sustainable Development*, *40*(2), 14. https://doi.org/10.1007/s13593-020-00617-4

Huss, C. P., Holmes, K. D., & Blubaugh, C. K. (2022). Benefits and Risks of Intercropping for Crop Resilience and Pest Management. *Journal of Economic Entomology*, *115*(5), 1350–1362. https://doi.org/10.1093/jee/toac045

Ilyas, H., & Masih, I. (2018). The effects of different aeration strategies on the performance of constructed wetlands for phosphorus removal. *Environmental Science and Pollution Research*, *25*(6), 5318–5335. https://doi.org/10.1007/s11356-017-1071-2

Islam, M. A., & Adjesiwor, A. T. (2018). Nitrogen fixation and transfer in agricultural production systems. *Nitrogen in Agriculture: Updates*, 95.

Izumi, Y., Okaichi, S., Awala, S. K., Kawato, Y., Watanabe, Y., Yamane, K., & Iijima, M. (2018). Water supply from pearl millet by hydraulic lift can mitigate drought stress and improve productivity of rice by the close mixed planting. *Plant Production Science*, *21*(1), 8–15. https://doi.org/10.1080/1343943X.2018.1428494

Järvinen, A., Himanen, S. J., Raiskio, S., & Hyvönen, T. (2022). Intercropping of insect-pollinated crops supports a characteristic pollinator assemblage. *Agriculture, Ecosystems & Environment*, *332*, 107930. https://doi.org/https://doi.org/10.1016/j.agee.2022.107930

Jensen, E. S., Carlsson, G., & Hauggaard-Nielsen, H. (2020). Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: A global-scale analysis. *Agronomy for Sustainable Development*, *40*(1), 5.

Justes, E., Bedoussac, L., Dordas, C., Frak, E., Louarn, G., Boudsocq, S., Journet, E.-P., Lithourgidis, A., Pankou, C., & Zhang, C. (2021). The 4C approach as a way to understand species interactions determining intercropping productivity. *Frontiers of Agricultural Science and Engineering*, *8*(3), 3.

Juventia, S. D., Selin Norén, I. L. M., van Apeldoorn, D. F., Ditzler, L., & Rossing, W. A. H. (2022). Spatio-temporal design of strip cropping systems. *Agricultural Systems*, *201*, 103455. https://doi.org/https://doi.org/10.1016/j.agsy.2022.103455

Kamh, M., Horst, W. J., Amer, F., Mostafa, H., & Maier, P. (1999). Mobilization of soil and fertilizer phosphate by cover crops. *Plant and Soil*, *211*, 19–27.

Keith, A. M., & Robinson, D. A. (2012). Earthworms as natural capital: ecosystem service providers in agricultural soils. *Economology Journal*, *2*, 91–99.

Kowalchuk, George. A., Buma, D. S., de Boer, W., Klinkhamer, P. G. L., & van Veen, J. A. (2002). Effects of above-ground plant species composition and diversity on the diversity of soil-borne microorganisms. *Antonie van Leeuwenhoek*, *81*(1), 509–520. https://doi.org/10.1023/A:1020565523615

Kremen, C., Williams, N. M., Aizen, M. A., Gemmill-Herren, B., LeBuhn, G., Minckley, R., Packer, L., Potts, S. G., Roulston, T., Steffan-Dewenter, I., Vázquez, D. P., Winfree, R., Adams, L., Crone, E. E., Greenleaf, S. S., Keitt, T. H., Klein, A.-M., Regetz, J., & Ricketts, T. H. (2007). Pollination and other ecosystem services produced by mobile organisms: a conceptual framework for the effects of land-use change. *Ecology Letters*, *10*(4), 299–314. https://doi.org/https://doi.org/10.1111/j.1461-0248.2007.01018.x

Laakso, J., Setälä, H., & Palojärvi, A. (2000). Influence of decomposer food web structure and nitrogen availability on plant growth. *Plant and Soil*, *225*, 153–165.

Lenderink, G., & van Meijgaard, E. (2008). Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nature Geoscience*, *1*(8), 511–514. https://doi.org/10.1038/ngeo262

Lepse, L., Dane, S., Zeipiņa, S., Domínguez-Perles, R., & Rosa, E. A. S. (2017). Evaluation of vegetable–faba bean (Vicia faba L.) intercropping under Latvian agro-ecological conditions. *Journal of the Science of Food and Agriculture*, *97*(13), 4334–4342. https://doi.org/https://doi.org/10.1002/jsfa.8239

Lepse, L., & Zeipiņa, S. (2023). *Increasing the sustainability of vegetable crops production by using intercropping*.

Li, B., Li, Y.-Y., Wu, H.-M., Zhang, F.-F., Li, C.-J., Li, X.-X., Lambers, H., & Li, L. (2016). Root exudates drive interspecific facilitation by enhancing nodulation and N2 fixation. *Proceedings of the National Academy of Sciences*, *113*(23), 6496–6501. https://doi.org/10.1073/pnas.1523580113

Li, C., Dong, Y., Li, H., Shen, J., & Zhang, F. (2016). Shift from complementarity to facilitation on P uptake by intercropped wheat neighboring with faba bean when available soil P is depleted. *Scientific Reports*, *6*(1), 18663. https://doi.org/10.1038/srep18663

Li, C., Stomph, T.-J., Makowski, D., Li, H., Zhang, C., Zhang, F., & van der Werf, W. (2023). The productive performance of intercropping. *Proceedings of the National Academy of Sciences*, *120*(2), e2201886120. https://doi.org/10.1073/pnas.2201886120

Li, S., & Kallas, Z. (2021). Meta-analysis of consumers' willingness to pay for sustainable food products. *Appetite*, *163*, 105239. https://doi.org/https://doi.org/10.1016/j.appet.2021.105239

LI, S. M., LI, L., ZHANG, F. S., & TANG, C. (2004). Acid Phosphatase Role in Chickpea/Maize Intercropping. *Annals of Botany*, *94*(2), 297–303. https://doi.org/10.1093/aob/mch140

Li, S., Ye, S., Liu, Z., Hassan, M. U., Huang, G., & Zhou, Q. (2024). How does intercropping contribute to soil organic carbon accumulation? A global synthesis. *Agriculture, Ecosystems & Environment*, *374*, 109173. https://doi.org/https://doi.org/10.1016/j.agee.2024.109173

Lichtenberg, E. M., Kennedy, C. M., Kremen, C., Batáry, P., Berendse, F., Bommarco, R., Bosque-Pérez, N. A., Carvalheiro, L. G., Snyder, W. E., Williams, N. M., Winfree, R., Klatt, B. K., Åström, S., Benjamin, F., Brittain, C., Chaplin-Kramer, R., Clough, Y., Danforth, B., Diekötter, T., … Crowder, D. W. (2017). A global synthesis of the effects of diversified farming systems on arthropod diversity within fields and across agricultural landscapes. *Global Change Biology*, *23*(11), 4946–4957. https://doi.org/https://doi.org/10.1111/gcb.13714

Ligtvoet, W. (2006). *Kaderrichtlijn water*. https://www.pbl.nl/sites/default/files/downloads/500072001.pdf

Lithourgidis, A. S., Dordas, C. A., Damalas, C. A., & Vlachostergios, D. N. (2011). Annual Intercrops: An Alternative Pathway for Sustainable Agriculture. *Australian Journal of Crop Science*, *5*(4), 396–410. https://search.informit.org/doi/10.3316/informit.281409060336481

Liu, M., Li, H., Song, J., Song, M., Qiao, N., Tian, Y., Liu, Y., & Niu, H. (2020). Interactions between intercropped Avena sativa and Agropyron cristatum for nitrogen uptake. *Plant and Soil*, *447*(1), 611–621. https://doi.org/10.1007/s11104-019-04389-z

Lokuge, N., & Anders, S. (2022). Carbon-credit systems in agriculture: a review of literature. *The School of Public Policy Publications*, *15*.

Louarn, G., Barillot, R., Combes, D., & Escobar-Gutiérrez, A. (2020). Towards intercrop ideotypes: non-random trait assembly can promote overyielding and stability of species proportion in simulated legume-based mixtures. *Annals of Botany*, *126*(4), 671–685. https://doi.org/10.1093/aob/mcaa014

Lundgren, R., Totland, Ø., & Lázaro, A. (2016). Experimental simulation of pollinator decline causes community-wide reductions in seedling diversity and abundance. *Ecology*, *97*(6), 1420–1430. https://doi.org/https://doi.org/10.1890/15-0787.1

Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrisik, P., Gitari, H., Brahmachari, K., Shankar, T., Bhadra, P., & Palai, J. B. (2021). Intercropping—A low input agricultural strategy for food and environmental security. *Agronomy*, *11*(2), 343.

Maitra, S., & Ray, D. P. (2019). Enrichment of biodiversity, influence in microbial population dynamics of soil and nutrient utilization in cereal-legume intercropping systems: A Review. *International Journal of Bioresource Science*, *6*(1), 11–19.

Manevska-Tasevska, G., Huang, V. W., Chen, Z., Jäck, O., Adam, N., Ha, T. M., Weih, M., & Hansson, H. (2024). Economic outcomes from adopting cereal-legume intercropping practices in Sweden. *Agricultural Systems*, *220*, 104064. https://doi.org/https://doi.org/10.1016/j.agsy.2024.104064

Martin, E. A., Feit, B., Requier, F., Friberg, H., & Jonsson, M. (2019). Chapter Three - Assessing the resilience of biodiversity-driven functions in agroecosystems under environmental change. In D. A. Bohan & A. J. Dumbrell (Eds.), *Advances in Ecological Research* (Vol. 60, pp. 59–123). Academic Press. https://doi.org/https://doi.org/10.1016/bs.aecr.2019.02.003

Matthews, H. D., & Wynes, S. (2022). Current global efforts are insufficient to limit warming to 1.5°C. *Science*, *376*(6600), 1404–1409. https://doi.org/10.1126/science.abo3378

Mayer, D. (2011). *The Complete Guide to Companion Planting: Everything You Need to Know to Make Your Garden Successful*. Atlantic Publishing Company.

McElroy, M. S., Papadopoulos, Y. A., Glover, K. E., Dong, Z., Fillmore, S. A. E., & Johnston, M. O. (2016). Interactions between cultivars of legume species (Trifolium pratense L., Medicago sativa L.) and grasses (Phleum pratense L., Lolium perenne L.) under different nitrogen levels. *Canadian Journal of Plant Science*, *97*(2), 214–225. https://doi.org/10.1139/cjps-2016-0130

Meyer, R., Cullen, B. R., Johnson, I. R., & Eckard, R. J. (2015). Process modelling to assess the sequestration and productivity benefits of soil carbon for pasture. *Agriculture, Ecosystems & Environment*, *213*, 272–280. https://doi.org/https://doi.org/10.1016/j.agee.2015.07.024

M'Gonigle, L. K., Ponisio, L. C., Cutler, K., & Kremen, C. (2015). Habitat restoration promotes pollinator persistence and colonization in intensively managed agriculture. *Ecological Applications*, *25*(6), 1557–1565. https://doi.org/https://doi.org/10.1890/14-1863.1

Mhadhbi, H., Djébali, N., Chihaoui, S., Jebara, M., & Mhamdi, R. (2011). Nodule Senescence in Medicago truncatula–Sinorhizobium Symbiosis Under Abiotic Constraints: Biochemical and Structural Processes Involved in Maintaining Nitrogen-Fixing Capacity. *Journal of Plant Growth Regulation*, *30*(4), 480–489. https://doi.org/10.1007/s00344-011-9210-3

Mikić, A., Ćupina, B., Mihailović, V., Krstić, Đ., Đorđević, V., Perić, V., Srebrić, M., Antanasović, S., Marjanović-Jeromela, A., & Kobiljski, B. (2012). Forage Legume Intercropping in Temperate Regions: Models and Ideotypes. In E. Lichtfouse (Ed.), *Sustainable Agriculture Reviews: Volume 11* (pp. 161–182). Springer Netherlands. https://doi.org/10.1007/978-94-007-5449-2_7

Mommer, L., Cotton, T. E. A., Raaijmakers, J. M., Termorshuizen, A. J., van Ruijven, J., Hendriks, M., van Rijssel, S. Q., van de Mortel, J. E., van der Paauw, J. W., Schijlen, E. G. W. M., Smit-Tiekstra, A. E., Berendse, F., de Kroon, H., & Dumbrell, A. J. (2018). Lost in diversity: the interactions between soil-borne fungi, biodiversity and plant productivity. *New Phytologist*, *218*(2), 542–553. https://doi.org/https://doi.org/10.1111/nph.15036

Mosquera-Losada, M. R., McAdam, J. H., Romero-Franco, R., Santiago-Freijanes, J. J., & Rigueiro-Rodróguez, A. (2009). Definitions and Components of Agroforestry Practices in Europe. In A. Rigueiro-Rodróguez, J. McAdam, & M. R. Mosquera-Losada (Eds.), *Agroforestry in Europe: Current Status and Future Prospects* (pp. 3–19). Springer Netherlands. https://doi.org/10.1007/978-1-4020-8272-6_1

Mousavi, S. R., & Eskandari, H. (2011). A general overview on intercropping and its advantages in sustainable agriculture. *Journal of Applied Environmental and Biological Sciences*, *1*(11), 482–486.

Nawaz, M. F., Bourrié, G., & Trolard, F. (2013). Soil compaction impact and modelling. A review. *Agronomy for Sustainable Development*, *33*(2), 291–309. https://doi.org/10.1007/s13593-011-0071-8

NOS. (2024, September 4). *Streep door natuurbeleid vorige kabinet, huidige stikstofaanpak provincies van tafel*. https://nos.nl/collectie/13901/artikel/2535751-streep-door-natuurbeleid-vorige-kabinet-huidige-stikstofaanpak-provincies-van-tafel

Ofosu-Budu, K. G., Ogata, S., & Fujita, K. (1992). Temperature effects on root nodule activity and nitrogen release in some sub-tropical and temperate legumes. *Soil Science and Plant Nutrition*, *38*(4), 717–726. https://doi.org/10.1080/00380768.1992.10416702

Pang, J., Wang, Y., Lambers, H., Tibbett, M., Siddique, K. H. M., & Ryan, M. H. (2013). Commensalism in an agroecosystem: hydraulic redistribution by deep-rooted legumes improves survival of a droughted shallow-rooted legume companion. *Physiologia Plantarum*, *149*(1), 79–90. https://doi.org/https://doi.org/10.1111/ppl.12020

Paustian, K., Six, J., Elliott, E. T., & Hunt, H. W. (2000). Management options for reducing CO2 emissions from agricultural soils. *Biogeochemistry*, *48*(1), 147–163. https://doi.org/10.1023/A:1006271331703

Peoples, M. B., Chalk, P. M., Unkovich, M. J., & Boddey, R. M. (2015). Can differences in 15N natural abundance be used to quantify the transfer of nitrogen from legumes to neighbouring non-legume plant species? *Soil Biology and Biochemistry*, *87*, 97–109. https://doi.org/https://doi.org/10.1016/j.soilbio.2015.04.010

Pérez Guerra, J. C., Coussens, G., De Keyser, A., De Rycke, R., De Bodt, S., Van De Velde, W., Goormachtig, S., & Holsters, M. (2010). Comparison of Developmental and Stress-Induced Nodule Senescence in Medicago truncatula. *Plant Physiology*, *152*(3), 1574–1584. https://doi.org/10.1104/pp.109.151399

Pirhofer-Walzl, K., Rasmussen, J., Høgh-Jensen, H., Eriksen, J., Søegaard, K., & Rasmussen, J. (2012). Nitrogen transfer from forage legumes to nine neighbouring plants in a multi-species grassland. *Plant and Soil*, *350*(1), 71–84. https://doi.org/10.1007/s11104-011-0882-z

Ponisio, L. C., M'Gonigle, L. K., & Kremen, C. (2016). On-farm habitat restoration counters biotic homogenization in intensively managed agriculture. *Global Change Biology*, *22*(2), 704–715. https://doi.org/https://doi.org/10.1111/gcb.13117

Ramos, D. de L., Bustamante, M. M. C., Silva, F. D. da S. e, & Carvalheiro, L. G. (2018). Crop fertilization affects pollination service provision – Common bean as a case study. *PLOS ONE*, *13*(11), e0204460-. https://doi.org/10.1371/journal.pone.0204460

Ramos-Jiliberto, R., Moisset de Espanés, P., & Vázquez, D. P. (2020). Pollinator declines and the stability of plant–pollinator networks. *Ecosphere*, *11*(4), e03069. https://doi.org/https://doi.org/10.1002/ecs2.3069

Raseduzzaman, Md., & Jensen, E. S. (2017). Does intercropping enhance yield stability in arable crop production? A meta-analysis. *European Journal of Agronomy*, *91*, 25–33. https://doi.org/https://doi.org/10.1016/j.eja.2017.09.009

Rashmi, I., Roy, T., Kartika, K. S., Pal, R., Coumar, V., Kala, S., & Shinoji, K. C. (2020). Organic and Inorganic Fertilizer Contaminants in Agriculture: Impact on Soil and Water Resources. In M. Naeem, A. A. Ansari, & S. S. Gill (Eds.), *Contaminants in Agriculture: Sources, Impacts and Management* (pp. 3–41). Springer International Publishing. https://doi.org/10.1007/978-3-030-41552-5_1

Ratnadass, A., Fernandes, P., Avelino, J., & Habib, R. (2012). Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: a review. *Agronomy for Sustainable Development*, *32*(1), 273–303. https://doi.org/10.1007/s13593-011-0022-4

Raza, M. A., Zhiqi, W., Yasin, H. S., Gul, H., Qin, R., Rehman, S. U., Mahmood, A., Iqbal, Z., Ahmed, Z., Luo, S., Juan, C., Liang, X., Gitari, H., Bin Khalid, M. H., Feng, Y., & Zhongming, M. (2023). Effect of crop combination on yield performance, nutrient uptake, and land use advantage of cereal/legume intercropping systems. *Field Crops Research*, *304*, 109144. https://doi.org/https://doi.org/10.1016/j.fcr.2023.109144

Richards, J. H., & Caldwell, M. M. (1987). Hydraulic lift: Substantial nocturnal water transport between soil layers by Artemisia tridentata roots. *Oecologia*, *73*(4), 486–489. https://doi.org/10.1007/BF00379405

Salem, Mansour. A., Bedade, D. K., Al-Ethawi, L., & Al-waleed, Samira. M. (2020). Assessment of physiochemical properties and concentration of heavy metals in agricultural soils fertilized with chemical fertilizers. *Heliyon*, *6*(10). https://doi.org/10.1016/j.heliyon.2020.e05224

Sánchez-Bayo, F., & Wyckhuys, K. A. G. (2019). Worldwide decline of the entomofauna: A review of its drivers. *Biological Conservation*, *232*, 8–27. https://doi.org/https://doi.org/10.1016/j.biocon.2019.01.020

Schiffers, K., Tielbörger, K., Tietjen, B., & Jeltsch, F. (2011). Root plasticity buffers competition among plants: theory meets experimental data. *Ecology*, *92*(3), 610–620. https://doi.org/https://doi.org/10.1890/10-1086.1

Schmidt, O., Clements, R. O., & Donaldson, G. (2003). Why do cereal–legume intercrops support large earthworm populations? *Applied Soil Ecology*, *22*(2), 181–190. https://doi.org/https://doi.org/10.1016/S0929-1393(02)00131-2

Sekiya, N., & Yano, K. (2004). Do pigeon pea and sesbania supply groundwater to intercropped maize through hydraulic lift?—Hydrogen stable isotope investigation of xylem waters. *Field Crops Research*, *86*(2), 167–173. https://doi.org/https://doi.org/10.1016/j.fcr.2003.08.007

Selosse, M.-A., Richard, F., He, X., & Simard, S. W. (2006). Mycorrhizal networks: des liaisons dangereuses? *Trends in Ecology & Evolution*, *21*(11), 621–628. https://doi.org/10.1016/j.tree.2006.07.003

Shah, A. N., Tanveer, M., Shahzad, B., Yang, G., Fahad, S., Ali, S., Bukhari, M. A., Tung, S. A., Hafeez, A., & Souliyanonh, B. (2017). Soil compaction effects on soil health and cropproductivity: an overview. *Environmental Science and Pollution Research*, *24*(11), 10056–10067. https://doi.org/10.1007/s11356-017-8421-y

Shantharam, S., & Mattoo, A. K. (1997). Enhancing biological nitrogen fixation: An appraisal of current and alternative technologies for N input into plants. *Plant and Soil*, *194*(1), 205–216. https://doi.org/10.1023/A:1004234315999

Shivanna, K. R., Tandon, R., & Koul, M. (2020). 'Global Pollinator Crisis' and Its Impact on Crop Productivity and Sustenance of Plant Diversity. In R. Tandon, K. R. Shivanna, & M. Koul (Eds.), *Reproductive Ecology of Flowering Plants: Patterns and Processes* (pp. 395–413). Springer Singapore. https://doi.org/10.1007/978-981-15-4210-7_16

Singh, D., Mathimaran, N., Boller, T., & Kahmen, A. (2019). Bioirrigation: a common mycorrhizal network facilitates the water transfer from deep-rooted pigeon pea to shallow-rooted finger millet under drought. *Plant and Soil*, *440*(1), 277–292. https://doi.org/10.1007/s11104-019-04082-1

Skinner, J. A., Lewis, K. A., Bardon, K. S., Tucker, P., Catt, J. A., & Chambers, B. J. (1997). An Overview of the Environmental Impact of Agriculture in the U.K. *Journal of Environmental Management*, *50*(2), 111–128. https://doi.org/https://doi.org/10.1006/jema.1996.0103

Skorupka, M., & Nosalewicz, A. (2021). Ammonia volatilization from fertilizer urea—a new challenge for agriculture and industry in view of growing global demand for food and energy crops. *Agriculture*, *11*(9), 822.

Spinoni, J., Vogt, J. V, Naumann, G., Barbosa, P., & Dosio, A. (2018). Will drought events become more frequent and severe in Europe? *International Journal of Climatology*, *38*(4), 1718–1736. https://doi.org/https://doi.org/10.1002/joc.5291

Steffan-Dewenter, I., Münzenberg, U., Bürger, C., Thies, C., & Tscharntke, T. (2002). SCALE-DEPENDENT EFFECTS OF LANDSCAPE CONTEXT ON THREE POLLINATOR GUILDS. *Ecology*, *83*(5), 1421–1432. https://doi.org/https://doi.org/10.1890/0012-9658(2002)083[1421:SDEOLC]2.0.CO;2

Stenberg, J. A., Heil, M., Åhman, I., & Björkman, C. (2015). Optimizing Crops for Biocontrol of Pests and Disease. *Trends in Plant Science*, *20*(11), 698–712. https://doi.org/10.1016/j.tplants.2015.08.007

Stomph, T., Dordas, C., Baranger, A., de Rijk, J., Dong, B., Evers, J., Gu, C., Li, L., Simon, J., Jensen, E. S., Wang, Q., Wang, Y., Wang, Z., Xu, H., Zhang, C., Zhang, L., Zhang, W.-P., Bedoussac, L., & van der Werf, W. (2020). Chapter One - Designing intercrops for high yield,

yield stability and efficient use of resources: Are there principles? In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 160, Issue 1, pp. 1–50). Academic Press. https://doi.org/https://doi.org/10.1016/bs.agron.2019.10.002

Strandsbjerg Tristan Pedersen, J., Duarte Santos, F., van Vuuren, D., Gupta, J., Encarnação Coelho, R., Aparício, B. A., & Swart, R. (2021). An assessment of the performance of scenarios against historical global emissions for IPCC reports. *Global Environmental Change*, *66*, 102199. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2020.102199

Stuiver, M., & Wiskerke, J. S. C. (2004). The VEL and VANLA environmental co-operatives as a niche for sustainable development. *Seeds of Transition: Essays on Novelty Production, Niches and Regimes in Agriculture. Royal Van Gorcum, Assen*, 119–148.

Tang, X., Zhang, C., Yu, Y., Shen, J., van der Werf, W., & Zhang, F. (2021). Intercropping legumes and cereals increases phosphorus use efficiency; a meta-analysis. *Plant and Soil*, *460*(1), 89–104. https://doi.org/10.1007/s11104-020-04768-x

Thilakarathna, M. S., McElroy, M. S., Chapagain, T., Papadopoulos, Y. A., & Raizada, M. N. (2016). Belowground nitrogen transfer from legumes to non-legumes under managed herbaceous cropping systems. A review. *Agronomy for Sustainable Development*, *36*(4), 58. https://doi.org/10.1007/s13593-016-0396-4

Thilakarathna, M. S., Papadopoulos, Y. A., Rodd, A. V, Grimmett, M., Fillmore, S. A. E., Crouse, M., & Prithiviraj, B. (2016). Nitrogen fixation and transfer of red clover genotypes under legume–grass forage based production systems. *Nutrient Cycling in Agroecosystems*, *106*(2), 233–247. https://doi.org/10.1007/s10705-016-9802-1

Tisdale, S. L., Nelson, W. L., & Beaton, J. D. (1985). *Soil fertility and fertilizers.*

Torralba, M., Fagerholm, N., Burgess, P. J., Moreno, G., & Plieninger, T. (2016). Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. *Agriculture, Ecosystems & Environment*, *230*, 150–161. https://doi.org/https://doi.org/10.1016/j.agee.2016.06.002

Tóth, G., Hermann, T., Da Silva, M. R., & Montanarella, L. (2016). Heavy metals in agricultural soils of the European Union with implications for food safety. *Environment International*, *88*, 299–309. https://doi.org/https://doi.org/10.1016/j.envint.2015.12.017

Trienekens, G. M. T. (1985). *Tussen ons volk en de honger: de voedselvoorziening, 1940-1945*. Wageningen University and Research.

Tsay, T. T., Wu, S. T., & Lin, Y. Y. (2004). Evaluation of Asteraceae plants for control of Meloidogyne incognita. *Journal of Nematology*, *36*(1), 36.

Tsialtas, I. T., Baxevanos, D., Vlachostergios, D. N., Dordas, C., & Lithourgidis, A. (2018). Cultivar complementarity for symbiotic nitrogen fixation and water use efficiency in pea-oat intercrops and its effect on forage yield and quality. *Field Crops Research*, *226*, 28–37. https://doi.org/https://doi.org/10.1016/j.fcr.2018.07.005

Valiente-Banuet, A., Rumebe, A. V., Verdú, M., & Callaway, R. M. (2006). Modern Quaternary plant lineages promote diversity through facilitation of ancient Tertiary lineages. *Proceedings of the National Academy of Sciences*, *103*(45), 16812–16817. https://doi.org/10.1073/pnas.0604933103

van Capelle, C., Schrader, S., & Brunotte, J. (2012). Tillage-induced changes in the functional diversity of soil biota – A review with a focus on German data. *European Journal of Soil Biology*, *50*, 165–181. https://doi.org/https://doi.org/10.1016/j.ejsobi.2012.02.005

Van Der Heijden, M. G. A., & Horton, T. R. (2009). Socialism in soil? The importance of mycorrhizal fungal networks for facilitation in natural ecosystems. *Journal of Ecology*, *97*(6), 1139–1150. https://doi.org/https://doi.org/10.1111/j.1365-2745.2009.01570.x

Van der Ploeg, J. D. (1987). *De verwetenschappelijking van de landbouwbeoefening.* (Issue 21). Landbouwuniversiteit Wageningen.

van der Wiel, K., Beersma, J., van den Brink, H., Krikken, F., Selten, F., Severijns, C., Sterl, A., van Meijgaard, E., Reerink, T., & van Dorland, R. (2024). KNMI'23 Climate Scenarios for the Netherlands: Storyline Scenarios of Regional Climate Change. *Earth's Future*, *12*(2), e2023EF003983. https://doi.org/https://doi.org/10.1029/2023EF003983

van Oort, P. A. J., Gou, F., Stomph, T. J., & van der Werf, W. (2020). Effects of strip width on yields in relay-strip intercropping: A simulation study. *European Journal of Agronomy*, *112*, 125936. https://doi.org/https://doi.org/10.1016/j.eja.2019.125936

van Ruijven, J., De Deyn, G. B., & Berendse, F. (2003). Diversity reduces invasibility in experimental plant communities: the role of plant species. *Ecology Letters*, *6*(10), 910–918. https://doi.org/https://doi.org/10.1046/j.1461-0248.2003.00516.x

Van Zanden, J. L. (1992). Mest en ploeg. In *Geschiedenis van de techniek in Nederland* (pp. 53–70).

Verret, V., Gardarin, A., Pelzer, E., Médiène, S., Makowski, D., & Valantin-Morison, M. (2017). Can legume companion plants control weeds without decreasing crop yield? A meta-analysis. *Field Crops Research*, *204*, 158–168. https://doi.org/https://doi.org/10.1016/j.fcr.2017.01.010

Voss-Fels, K. P., Snowdon, R. J., & Hickey, L. T. (2018). Designer Roots for Future Crops. *Trends in Plant Science*, *23*(11), 957–960. https://doi.org/10.1016/j.tplants.2018.08.004

Wang, K.-H., Hooks, C. R. R., & Marahatta, S. P. (2011). Can using a strip-tilled cover cropping system followed by surface mulch practice enhance organisms higher up in the soil food web hierarchy? *Applied Soil Ecology*, *49*, 107–117. https://doi.org/https://doi.org/10.1016/j.apsoil.2011.06.008

Wang, Z. (2024). *Productivity and resource use efficiency in strip intercropping in the Netherlands* [WUR]. https://doi.org/https://doi.org/10.18174/653790

Wang, Z., Dong, B., Stomph, T. J., Evers, J. B., L. van der Putten, P. E., Ma, H., Missale, R., & van der Werf, W. (2023). Temporal complementarity drives species combinability in strip intercropping in the Netherlands. *Field Crops Research*, *291*, 108757. https://doi.org/https://doi.org/10.1016/j.fcr.2022.108757

Wang, Z.-G., Jin, X., Bao, X.-G., Li, X.-F., Zhao, J.-H., Sun, J.-H., Christie, P., & Li, L. (2014). Intercropping Enhances Productivity and Maintains the Most Soil Fertility Properties Relative to Sole Cropping. *PLOS ONE*, *9*(12), e113984-. https://doi.org/10.1371/journal.pone.0113984

Weemstra, M., Mommer, L., Visser, E. J. W., van Ruijven, J., Kuyper, T. W., Mohren, G. M. J., & Sterck, F. J. (2016). Towards a multidimensional root trait framework: a tree root review. *New Phytologist*, *211*(4), 1159–1169. https://doi.org/https://doi.org/10.1111/nph.14003

Wenda-Piesik, A., & Synowiec, A. (2021). Productive and Ecological Aspects of Mixed Cropping System. In *Agriculture* (Vol. 11, Issue 5, p. 395). MDPI.

Westphal, C., Steffan-Dewenter, I., & Tscharntke, T. (2003). Mass flowering crops enhance pollinator densities at a landscape scale. *Ecology Letters*, *6*(11), 961–965. https://doi.org/https://doi.org/10.1046/j.1461-0248.2003.00523.x

Wetzel, W. C., Kharouba, H. M., Robinson, M., Holyoak, M., & Karban, R. (2016). Variability in plant nutrients reduces insect herbivore performance. *Nature*, *539*(7629), 425–427. https://doi.org/10.1038/nature20140

Williams, E. J., Hutchinson, G. L., & Fehsenfeld, F. C. (1992). NOx And N2O Emissions From Soil. *Global Biogeochemical Cycles*, *6*(4), 351–388. https://doi.org/https://doi.org/10.1029/92GB02124

Withers, P. J. A., Neal, C., Jarvie, H. P., & Doody, D. G. (2014). Agriculture and eutrophication: where do we go from here? *Sustainability*, *6*(9), 5853–5875.

Wyland, L. J., Jackson, L. E., Chaney, W. E., Klonsky, K., Koike, S. T., & Kimple, B. (1996). Winter cover crops in a vegetable cropping system: Impacts on nitrate leaching, soil water, crop yield, pests and management costs. *Agriculture, Ecosystems & Environment*, *59*(1), 1–17. https://doi.org/https://doi.org/10.1016/0167-8809(96)01048-1

Xiao, X., Cheng, Z., Meng, H., Khan, M. A., & Li, H. (2012). Intercropping with garlic alleviated continuous cropping obstacle of cucumber in plastic tunnel. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, *62*(8), 696–705. https://doi.org/10.1080/09064710.2012.697571

Yang, T., Siddique, K. H. M., & Liu, K. (2020). Cropping systems in agriculture and their impact on soil health-A review. *Global Ecology and Conservation*, *23*, e01118. https://doi.org/https://doi.org/10.1016/j.gecco.2020.e01118

Yang, Y. (2016). *Crop yields in intercropping: meta-analysis and virtual plant modelling.* Wageningen University and Research.

Yarnell, R. W., & Pettett, C. E. (2020). Beneficial land management for hedgehogs (Erinaceus europaeus) in the United Kingdom. *Animals*, *10*(9), 1566.

Yildirim, E., & Guvenc, I. (2005). Intercropping based on cauliflower: more productive, profitable and highly sustainable. *European Journal of Agronomy*, *22*(1), 11–18. https://doi.org/https://doi.org/10.1016/j.eja.2003.11.003

Yu, Y., Stomph, T.-J., Makowski, D., & van der Werf, W. (2015). Temporal niche differentiation increases the land equivalent ratio of annual intercrops: A meta-analysis. *Field Crops Research*, *184*, 133–144. https://doi.org/https://doi.org/10.1016/j.fcr.2015.09.010

Zadoks, J. C. (1985). *Landbouw tussen ecologie en economie*.

Zhou, S., Yu, B., & Zhang, Y. (2024). Global concurrent climate extremes exacerbated by anthropogenic climate change. *Science Advances*, *9*(10), eabo1638. https://doi.org/10.1126/sciadv.abo1638

Zhou, Y., Cen, H., Tian, D., Wang, C., & Zhang, Y. (2019). A tomato and tall fescue intercropping system controls tomato stem rot. *Journal of Plant Interactions*, *14*(1), 637–647. https://doi.org/10.1080/17429145.2019.1689582

Zhu, J., van der Werf, W., Anten, N. P. R., Vos, J., & Evers, J. B. (2015). The contribution of phenotypic plasticity to complementary light capture in plant mixtures. *New Phytologist*, *207*(4), 1213–1222. https://doi.org/https://doi.org/10.1111/nph.13416

Zhu, S., & Morel, J.-B. (2018). Molecular Mechanisms Underlying Microbial Disease Control in Intercropping. *Molecular Plant-Microbe Interactions®*, *32*(1), 20–24. https://doi.org/10.1094/MPMI-03-18-0058-CR

Appendix

Methodology

Several methods have been used during this project. The main part of the research for this project consists of literature studies on the subject to answer the research questions posed above. Interviews have been conducted to get the opinions of people with expert knowledge on this topic, such as conventional farmers, intercropping farmers, governing bodies, and researchers. Nine interviews have been done in total, including four researchers, three organic farmers, one conventional farmer and one policymaker. These interviews have been recorded and afterwards been transcribed using various AI powered tools.

Next to that, several activities have been undertaken to increase knowledge on the topic of intercropping. These include excursions to see how intercropping is currently applied in agriculture, but also three lectures from a conference on intercropping have been attended. Based on the information gained from these activities, it was possible to better understand and answer our research questions.

The interviews have been conducted in duos, were recorded, and transcribed afterward, or notes have been taken during the interview if the interviewee prefers that over being recorded. The interviews were performed in English or Dutch, depending on the preference of the interviewee. A base list of questions has been made and used for every interview so the results of the interviews could be compared.

The ACT team has expert knowledge in the fields of plant sciences, soil science, hydrology, and nature conservation. During the project the team has used their expertise to form the best advice within the timeframe. The project had various aspects that are relevant to different experts within our team. Literature research is well within all our capabilities, and interviewing was something we were confident in bringing to a good end.

Methodological reflections

During our research we encountered multiple perspectives which led to a change in direction to better accommodate our commissioners' interests. We discovered that there was little research about an optimal crop pairing and that exploring ideal pairings seemed less manageable than we had anticipated. One of the factors was the variability in (a)biotic factors across the Netherlands and their effects on pairing performance, along with the sheer complexity of poorly understood plant interactions. Additionally, Van Apeldoorn stressed that finding "optimal pairings" was less important (given the current state of Dutch agriculture) than we had envisioned. After a brainstorming session, we shifted the focus to benefits and challenges of intercropping implementation, rather than benefits and challenges of "optimal" intercropping mixtures. We still included crop combinations and highlighted their respective effects but discontinued our explorative research on "optimal pairings". We believe this shift resulted in a more insightful and usable result for our commissioner and a more feasible project within the available timeframe.

Research questions

In agreement with our commissioner, the underlying research questions were changed, while we kept the original main research question. Below is an overview of the adjustments.

- Original research question 1: *What are the common intercropping combinations already used in Europe?*
- Revised research question 1: What are the common crop combinations already used or researched in Europe for intercropping systems?

With the inclusion of researched combinations, we broadened the scope of the project. This allowed the addition for more literature and probable future combinations rather than focusing on current practices.

- Original research question 5: *What are the current technological bottlenecks for these intercropping combinations in the Netherlands?*
- Revised research question 5: *What are the current technological bottlenecks for intercropping in the Netherlands?*
- Original research question 6: *What are the current socio-economic bottlenecks for these intercropping combinations in the Netherlands?*
- Revised research question 6: *What are the current socio-economic bottlenecks for implementing intercropping in the Netherlands?*

The change of perspective from combinations to the implementation of intercropping in questions 5 and 6 suited the main research question better. This shifted the focus from a quantitative output-based perspective to a more holistic approach.

- Original research question 2: *What are the agricultural performances of these intercropping combinations (yield, growth size, cost…)?*
- Revised research question 2: *What are the mechanisms underpinning the agricultural benefits of intercropping?*

Due to a shift in focus, the original research question 2 was not relevant anymore. The revised question addresses the beneficial mechanisms behind intercropping, which also allowed us to include a plant trait perspective, aligning it more with the interests of our commissioner.

- Original research question 4: *What are the ecological benefits of certain intercropping combinations?*
- Revised research question 4: *What are the ecological benefits of intercropping?*

Similar to questions 5 and 6, we changed the perspective and broadened the scope, by looking at intercropping in general, rather than focusing on a set of optimal crop combinations.

- Original research question 3: *What are the most suitable intercropping combinations for local environmental factors, such as soil type, SOM, nutrient ratio, and groundwater table?*
- Revised research question 3: *What are the most suitable intercropping combinations for local environmental factors?*

Question 3 has been revised to a more concise sentence.

Lastly, the order of the research questions has been changed such that they flow from plant interactions and specific details of intercropping to a larger systems-based view on bottlenecks to transition.

Interviews

In the proposal, we stated that we would anonymise the interviews unless agreed upon differently. However, all participants agreed on being mentioned by name, and did not need to be anonymised. Therefore, the names of all participants are included in the report.

The number of proposed interviews per category also differed. We anticipated performing 8 interviews in total and 2 of each category: researchers, intercropping farmers, conventional farmers and governing bodies. While a total of 8 interviews were held (one was a combination of 2 interviewees) they followed the following distribution: 4 researchers, 3 intercropping farmers, 1 conventional farmer and 1 policy maker. Both researchers and intercropping farmers often had online contact information and were usually very responsive. Conventional farmers were harder to reach since their contact information was usually private. We got in contact with a conventional farmer through his nephew, intercropping farmer A. Jurrius. Reaching policymakers proved to be a challenge as well. We often were refused, and e-mails were left unanswered. Therefore, the latter categories had only 1 interview.

Ideally, we would have more interviews per category. Only having one perspective from a policymaker and a conventional farmer, lacks the nuance necessary for a balanced, multi-perspective report. Since more interviews could be conducted with researchers and intercropping farmers, their findings allowed for a more detailed and nuanced view. Especially since researchers and farmers also had different perspectives on each other. Doing interviews proved to be a good way of data collection for the socio-economic angle, as this was less touched upon in the literature.

Output

Our initial output would have consisted of a report, accompanied by a "determination key" to guide farmers on optimal crop combinations based on soil type or anticipated benefits (increased yield, decreased fertiliser needs, biological pest control). After the change in perspective on "optimal pairings", this "determination key" did not appear feasible or relevant anymore. We decided to make a visual compendium instead, where all aspects of our report are visualised in a comprehensive way, as well as a table summarising similar and diverging views of our interviewees and mentioned bottlenecks. This change was presented to and approved by the commissioner.

Ethical Implications

Our proposed research activities primarily involved literature research of cropping systems and conducting stakeholder interviews. These activities and the subsequent report of our findings was carried out following the Netherlands Code of Conduct for Research Integrity. Of particular ethical concern was the undertaking of stakeholder interviews. Ineffective lengthy interviews carry the risk of exhausting or wasting the interviewees' time. Poor interview conduct could damage stakeholder-researcher relations indefinitely, hindering future research endeavours. While cropping systems in itself may not be a sensitive topic, it is important to recognise that they may form the basis of farmer livelihoods. Additionally, current Farmer-Government climate needed to be considered while conducting the interviews.

To ensure safe, ethical, and effective interviews, participants were be informed of the project purpose and outcomes as well as why their input had been sought out and how the data they provide would be handled. Participant anonymity, privacy, and confidentiality was ensured (unless agreed upon differently) by removing names, addresses, and other identifying information from collected data. Participants were made aware of the voluntary nature of the interview, and the "training" aspect of the ACT project. If permission was given to make an audio recording of the interview, this data was deleted after transcription (transcription performed, with consent, using artificial intelligence).