TOWARDS DIVERSIFIED INDUSTRIAL CROPPING SYSTEMS?

LENORA LOUISE EVENS DITZLER

Propositions

1. Diversification should be considered both a goal in itself and a means to an end in agricultural research.
   (this thesis)

2. Intermediate-resolution crop diversity is optimal for meeting current societal demands, but high-resolution crop diversity provides greater learning opportunities.
   (this thesis)

3. Scientists should spend more time out standing in the field and less time trying to be outstanding in the field.

4. Presenting scientific research in an art museum has more societal impact than publishing an article in a peer-reviewed journal.

5. The term ‘nature-inclusive agriculture’ perpetuates dualisms which undermine sustainability goals.

6. Monocultures will dominate agriculture as long as patriarchy dominates society.

Propositions belonging to the thesis, entitled

Towards Diversified Industrial Cropping Systems?

Lenora Louise Evens Ditzler
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Towards Diversified Industrial Cropping Systems?

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Towards Diversified Industrial Cropping Systems?

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For my grandmothers,
radical women of their time

Contents

Chapter 1

General introduction

But the sower
going forth to sow sets foot
into time to come, the seeds falling
on his own place.

Wendell Berry, The Seeds (1971)

1.1. Imagining the future of farming

In 1970, the *National Geographic* magazine published an article titled "The Revolution in American Agriculture." The article was accompanied by an artist's rendition of "the farm of the future" (Fig. 1.1). The caption under the image describes an ultramodern farmhouse, a computer-driven control tower, and a remote-controlled combine. Human engagement is depicted as surveillance from behind glass walls. The vision is punctuated by vast notions of scale, efficiency, and technological prowess: we see a 10-mile-long field of wheat being harvested by a massive combine and a jumbo jet spraying acres of soy. Now zoom ahead to 2022, the time of writing this thesis. In the Netherlands, another agro-future is being imagined, this time unfolding on the soils of the Flevopolder. The Dutch 'Farm of the Future' is conceived as a proof of principle, a sort of prototype and field lab where promising practices and technologies are tested at farmer-relevant scales. The farm's website[1] shows images of vibrant fields of diverse crops cultivated in strips, interspersed with rainbows of wildflowers and the occasional drone. Its motto reads, "Dichterbij dan je denkt" or, "Closer than you think." The future, that is.

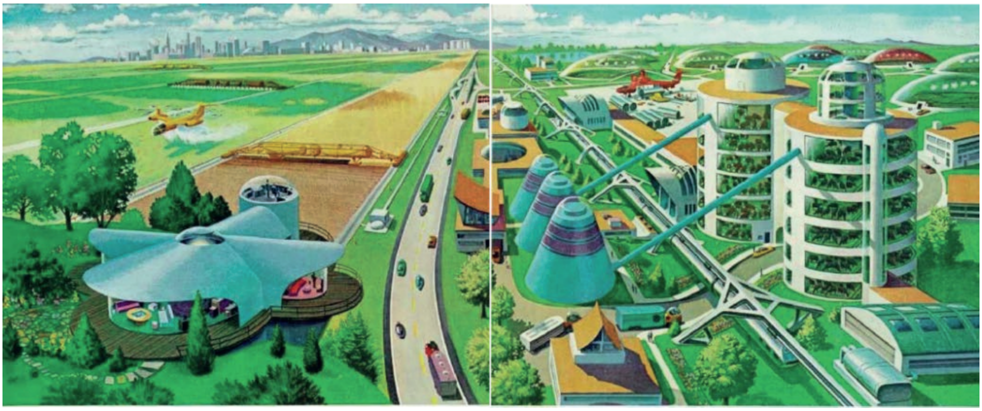

Figure 1.1. "The farm of the future," as imagined by David Meltzer for *National Geographic* magazine, February 1970.

Imagining and anticipating the future—population changes, consumption changes, technological changes, regulatory changes—has factored heavily into the motivations and justifications for agricultural research during the last several decades, but has not always been effective for meeting sustainability targets (Bai et al. 2016). Broadly speaking, anticipatory objectives fueled the coevolution of heavy machinery, specialized and input-intensive farming systems, and 'feed the world' narratives which characterized the Green Revolution and continue to characterize industrial farming in the Global North. As the impacts of climate change loom more presently over a growing swath of the earth while the population continues to swell and

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[1] www.farmofthefuture.nl

finite resources dwindle, anticipating and planning for the future has become an increasingly urgent task for farmers and agricultural systems scientists.

Today the goals driving the future farming narrative have started to shift, encompassing a set of demands on agriculture that now extends far beyond producing food for the masses. Yet, following the techno-fix vision presented in the *National Geographic*, dualist perspectives on viable pathways for agriculture continue to dominate mainstream debates about how to imagine the future of farming, perspectives in which production aims are often assumed to be at odds with environmental aims and technological acceleration at odds with ecological ways of working and knowing. These perspectives can be found in the 'half earth' vs. 'sharing the planet' debate (Immovilli and Kok 2020; Mehrabi et al. 2018), the Wizard and the Prophet allegory (Mann 2018), and projections pitting organic agriculture against conventional or agroecological against industrial (Connor 2008; Kremen et al. 2012). Each polarized vision produces a different imagination of the future and what role technology might have in it (Daum 2021), and a different set of winners and losers (Montenegro de Wit 2021; Wyborn et al. 2020).

The work in this thesis is framed by a different proposal: rather than drawing hard lines—between nature and agriculture, technology and ecology, production and environment—and imagining opposing scenarios, I instead ask what range of possibilities might make sense for moving towards various objectives and in different timeframes. *(How) can we design cropping systems that qualify as both industrial and agroecological? That center both production and ecology, both ecology and technology?* I explore this middle ground by engaging two modes of imagining solutions for the challenges facing agriculture, using what Scheffer et al. (2015) have called "dual thinking." The first mode is about reasoning and working inside the box: how can we improve the present or near present, which can be imagined using the same tools, techniques, and understandings of how things work that we already use today, by rearranging current systems and practices? The second is about creative association—abandoning the box and adopting long-term thinking, through what could be understood as "speculative design" (Dunne and Raby 2013; Escobar 2018) or "imaginative scenarios" (Pereira et al. 2019): what solutions can we imagine when we take the long view, make novel connections, and extend our sights beyond the limits of what is currently realistic? This thesis utilizes both modes: the research questions, methods, and analyses I employ aim to facilitate moving back and forth between everyday practice and speculation, informing each other and in doing so positioning each (and their interplay) as relevant and necessary for meeting the multifaceted demands placed on near and distant future farming systems.

1.2. Beyond monoculture thinking

The image published by *National Geographic* in 1970 nicely illustrates the intensification paradigm of industrial farming which has dominated the way agriculture is conceived in the Global North. By industrial farming generally, and industrial crop production specifically, I mean production systems which are characterized by high levels of mechanization, intensive production capacities, strong dependence on external inputs (agrochemicals in conventional systems), and high levels of specialization. Since the image in Fig. 1.1 was published, industrial farming has achieved much for society in terms of production, but also played a major role in the overstepping of planetary boundaries (Campbell et al. 2017; Rockström et al. 2009). Key to agriculture's culpability in accelerating unfavorable global change is the monocultural mode of production which dominates industrially-farmed fields (IPES-Food 2016).

The term 'monoculture' can refer to repeated cultivation of the same crop in the same field from season to season, or to sole-cropped fields which are homogenously sown in space and progress through a crop rotation in time. In this thesis I use the term monoculture to mean the latter: a (large-scale) field—time unit cropped with a sole crop. In Europe, a historical focus on specialization in arable cropping has resulted in the co-evolution of industrial farming practices and monocultures as plant breeders, machine developers, and agro-chemical corporations have sought to meet the self-reinforcing demands of uniformity, efficiency, and ever-higher production targets (Fitzgerald 2003; Kloppenburg 2005; Schmitz and Moss 2015). This co-evolution has resulted in the dominance of low-diversity production systems in industrialized contexts, and monocultural production is currently the primary mode of cultivation utilized in Europe (van Vliet et al. 2015).

The prevalence of industrial monoculture landscapes has led to a cascading array of negative externalities and vulnerabilities, and mounting societal pressures to remedy these. Decades of focus on intensification in industrial monocultures has allowed agroecosystem managers to maximize productivity by maintaining production systems in an exploitative state of "coerced resilience" (Patzek 2008; Rist et al. 2014), but this state is vulnerable to pest and disease outbreaks, extreme weather, and market fluctuations, and highly dependent on inputs, many of which are non-renewable. The environmental externalities from industrial monocultures include soil erosion, water pollution, finite resource depletion, and habitat loss, among others (Campbell et al. 2017; Haddad et al. 2015). In response, policy measures have focused on minimizing damages, for example through limits on fertilizer application and caps on allowable nutrient loads in run-off water. To accommodate these constraints, agronomic research has concentrated on fine-tuning the industrial monoculture approach, resulting in precision technologies which reduce impacts but reinforce the monocultural paradigm (Kuch et al. 2020; Miles 2019).

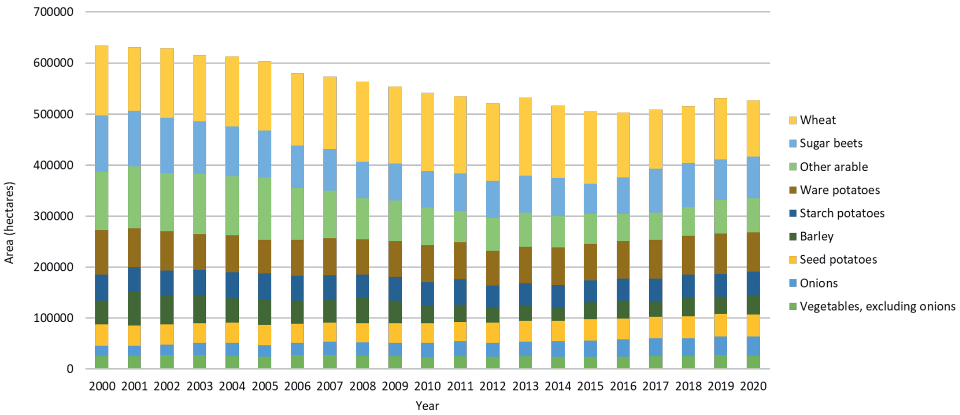

Figure 1.2. Area of arable and vegetable crops grown in the Netherlands, from 2000-2020. Vegetables (excluding onions) includes in order of area occupied: brussels sprouts, asparagus, leek, cabbages, strawberry, cauliflower, lettuce, and broccoli. Between 2000 and 2020, the average utilized agricultural area per arable farm in the Netherlands increased from 32.5 hectares to 41.7 hectares. Data retrieved from CBS-Landbouwtelling (2020).

In the European Union (EU), the ambitions of the Green Deal and in particular the Farm to Fork Strategy set out high targets for reducing the environmental impacts of agriculture and illustrate public acceptance of the need for a more sustainable way of doing farming (EC 2020). The research in this thesis is positioned in the Netherlands where, as elsewhere in Europe, industrial farming is the norm and agricultural landscapes are composed of large fields made up of a small selection of crops (Fig. 1.2) (CBS-Landbouwtelling 2020). Currently, nitrogen emissions and biodiversity loss are at the forefront of public debates about Dutch agriculture's ecological impact (Schouten 2019; van der Wal 2022). The expectations placed on Dutch (and all European) farmers have thus expanded to include not only producing food, feed, and fiber, but also producing associated ecological benefits for future and present generations, and even remedying past harms (Schreefel et al. 2020). Policy makers are now looking to agricultural researchers to provide solutions that can deliver the expected yields within an even tighter set of environmental constraints while also expanding the delivery of ecological benefits. And so many people are asking, *what are possible alternatives to the industrial monoculture approach, and do they work?* (Re)introducing crop diversity into industrial farming systems is one of these alternatives.

1.3. Diversified industrial cropping systems?

This thesis centers crop diversification as a potential lever for reducing the negative ecological impacts and increasing the multifunctionality of industrialized crop production in the European and specifically Dutch context. Crop diversification refers to the introduction of agrobiodiversity and heterogeneity into monocultural crop production systems through practices which may include various forms of intercropping, rotation extension, multiple cropping, or any combination of these (Messean et al. 2021). In the time since I began the research, multiple comprehensive meta-analyses have been published which illuminate both the abundance of crop diversity research being done worldwide and the potential of crop diversification to address the demands placed on European farmers (Beillouin et al. 2021; Botzas-Coluni et al. 2021; Gu et al. 2021; Tamburini et al. 2020). In the same timeframe, a broad consortium of researchers has been investigating the prospects and challenges of crop diversification within a cluster of six EU Horizon 2020 projects[2]. Those projects, and this thesis research, share the common assumption that crop diversity holds promise for meeting the multifaceted demands placed on European farmers.

The evidence supporting this assumption is strong: the aforementioned meta-analyses indicate that agrobiodiverse cropping systems (i.e. those incorporating intercropping, crop rotations, agroforestry, and/or other forms of crop diversification) can produce more associated ecological benefits than comparable sole-crop references without yield penalties (Tamburini et al. 2020). In some cases, yield gains are also achieved (Li et al. 2020; Yu et al. 2015). In addition to ecological benefits, other studies have found that crop diversification can stabilize food production over time (Renard and Tilman 2019), and reduce potential yields gaps in the transition from conventional to organic (Ponisio et al. 2015). Much of this research has taken place outside of Europe and in low-input systems (where in particular the yield benefits of crop diversification are more evident (MacLaren et al. 2022)), so it remains an open question whether the same trends hold in a place like the Netherlands—in other words, whether a move towards diversified industrial crop production can be validated.

Within Europe, the diversification methods being implemented and studied are not very diverse, comprised primarily of crop rotation and cereal—grain legume intercropping (Hufnagel et al. 2020; Stomph et al. 2020). Researchers already know a lot about the benefits of both crop rotations and grain legumes from a variety of perspectives and they are both valuable diversification tools, but there is a much broader range of possible diversification methods—and crops—that have not yet been sufficiently examined in Europe. Just as farmers are often locked into monocultural production modes and narrow rotations (Magrini et al. 2019; Meynard et al. 2018), so too can research be locked in (Vanloqueren and Baret 2009).

The research presented in this thesis is part of a larger effort at moving beyond the industrial monoculture and unlocking a wider range of solutions (IPES-Food 2016; Messean et al. 2021). It is embedded within two of the EU Horizon 2020 crop diversification cluster projects, DiverIMPACTS and LegValue. Motivating both projects is the premise that before agrobiodiverse cropping systems can find a place in mainstream industrial European farming, further research into the ecological and production potential of multiple diversification methods, in multiple pedo-climactic zones and with multiple crops, is needed. Taking a systems view, both DiverIMPACTS and LegValue posit that the question of whether crop diversification "works" must also be examined at all levels of the value chain. A multi-level approach is built into the structure of the projects, with work packages focused on field, farm, community, institutional,

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[2] www.cropdiversification.eu

regional, and national levels. Mobilizing the benefits of diversity implies a wide range of concurrent impacts and necessary system changes that span far beyond cultivation practices (Antier et al. 2021), but the change is ultimately grounded in the farm field. As part of the DiverIMPACTS and LegValue field experiment networks which seek to quantify the benefits of crop diversity (LegValue looking specifically at diversification through including legumes in rotations, DiverIMPACTS at all forms of crop diversification), the research in this thesis focuses on crop production at the field level: where society's imagined farms of the future are first made tangible by farmers.

1.4. Mono, strip, pixel

As described in Section 1.1, I utilize two temporal scales for thinking about solutions to the challenges facing agriculture which involve looking towards the near and distant future. Both approaches stem from the recognition that we are in the midst of an agricultural transition in which the externalities of the industrial monoculture paradigm are being questioned, but a new mode of conceiving farming has not yet gained a foothold in the mainstream and non-monocultural solutions remain niche (Darnhofer 2015; Dumont et al. 2020; Geels 2002). This research conceives of one possible transition pathway for moving from industrial monocultures towards something more multifunctional and sustainable, taking field-level crop diversification as the driving lever. I work with three steps on this pathway, which are conceptually and practically defined as *mono*, *strip*, and *pixel* (Fig. 1.3). ***Mono*** refers to the status quo, where industrial agriculture is now: large-scale sole-cropped fields. ***Strip*** refers to strip cropping, the practice of growing two or more crops in alternating multi-row strips wide enough to be cultivated independently but narrow enough for ecological interaction between strips. *Strip* represents a currently feasible or near-future step which could be made within the knowledge, practice, and assessment structures already in place. ***Pixel*** refers to the pixel cropping cultivation method, which involves planting many different food and service crops in a patchwork-like arrangement composed of small (0.25 m^2 – 2.25 m^2) crop patches. *Pixel* represents one future-looking imagination for how industrial farming could be rearranged towards higher-resolution agrobiodiversity and ecological relations.

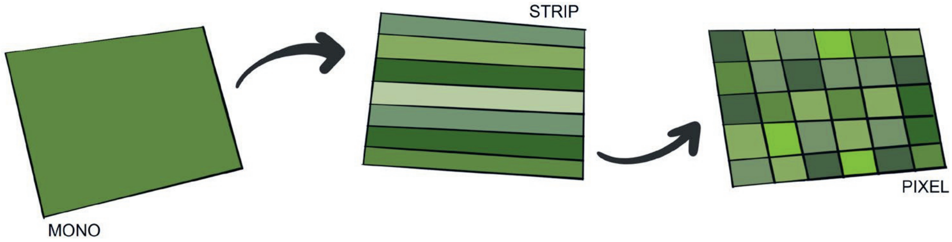

Figure 1.3. A transition pathway towards diversified industrial cropping systems, explored theoretically and empirically in this thesis. Each step shows a single farm field, each shade of green a different crop or variety.

Each of these steps involves an increase in the resolution of homogeneous field management units, and thus implies an array of associated changes to and impacts on the performance of agroecological systems and to the way they are managed, and these are context dependent. In this thesis I explore the three steps empirically and theoretically within the perspective of European open-field cropping systems broadly and Dutch organic arable cropping systems specifically. In the Netherlands, crop cultivation is highly productive, its ecological impacts highly scrutinized, and its labor intensively mechanized, so the particularities of diversification changes and impacts relate largely to questions of production levels, ecological performance, and technological compatibility; I seek to assess these three concerns at each conceptual and practical step. Key questions that emerge in the Dutch context—and that frame this thesis—are:

- *Do these methods (steps) work?*
- *How much crop diversity (how big a step) is needed to achieve both production and ecological goals?*
- *And what does cultivating that much diversity mean for management and technology?*

Asking *does it work?* requires delineating further questions: 'work' according to what measures of success, and for whom? In this thesis I engage with a range of measures of success which fall primarily under the umbrella of agroecosystem services (AES). These I define as the life-supporting services, i.e. the (ecological) benefits, that humans obtain from the functioning of agroecosystems (Zhang et al. 2007). AES can be further described as either input or output services (Duru et al. 2015b): input services refer to those that are provided to/within the agroecosystem itself and facilitate its functioning (e.g. soil fertility, crop protection, resource use efficiency, pollination), and output services refer to those that are provided by the functioning of the agroecosystem and which serve cycles and organisms beyond the agroecosystem (e.g. production, climate change mitigation, associated biodiversity, cultural services). The delivery of each AES can be estimated via a variety of measurable indicators, and it is these indicators that I assess at each step of the mono—strip—pixel pathway, with the understanding that they are representative of a particular contextual moment in time and of only a partial view of more complex system processes (Jax et al. 2018). The indicators I use include soil fertility, crop yield and quality, pest and disease mitigation, weed control, and biodiversity; these are explained in detail in the relevant chapters. Beyond empirical AES indicators, I also qualitatively assess the appropriateness of technological solutions for dealing with management complexity at higher crop diversity resolutions through engagement with various stakeholders in collaborative design projects. By examining this array of "does it work" indicators, I aim to broaden the scope of the *whom* for which the performance of each system/step is assessed.

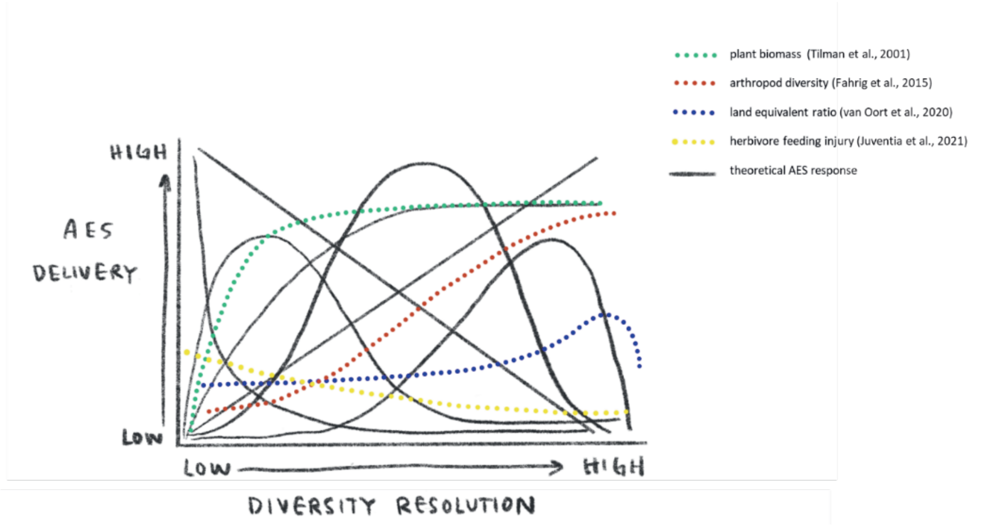

Figure 1.4. Some measured (dotted lines) and theoretical (solid lines) response relationships between resolution of diversity in production systems and agroecosystem service (AES) delivery. Green dotted line shows grassland plant biomass (y axis) in response to system species richness (x axis), adapted from Tilman et al. (2001); red dotted line shows spider Gamma diversity (y axis) in response to field size (log scale, x axis), adapted from Fahrig et al. (2015); blue dotted line shows the land equivalent ratio of a maize—wheat intercrop with one row of maize (y axis) in response to the width of the intercropped wheat strip (x axis), adapted from van Oort et al. (2020); yellow dotted line shows herbivore feeding injury to individual cabbage heads (y axis) in response to cropping system taxonomic richness (x axis), adapted from Juventia et al. (2021).

Unravelling relationships between the resolution of diversity in the cropping system, the AES it delivers, and the resulting management complexity is of particular interest in the transition pathway when moving away from industrial monocultures, as these relationships will determine the answer to the question *how much diversity is needed?* Crop diversification is about planned heterogeneity—field design elements chosen to achieve different functional system outputs (e.g. production, insect habitat, aesthetic quality)—which makes response relationships between diversity resolution and AES delivery potentially different than in natural ecosystems (Loreau et al. 2001). There is some evidence to suggest that higher-resolution production systems are associated with increases in certain services, for example more biomass production in more diverse grasslands (Tilman et al. 2001), higher arthropod species diversity in smaller fields (Fahrig et al. 2015), higher grain production in narrower intercrops (van Oort et al. 2020), and less pest damage in systems with higher in-field crop diversity (Juventia et al. 2021) (Fig. 1.4, dotted lines). For these and for other services, the response relationships tend to be variable depending on the crops, soil types, pedoclimatic regions, input levels, and spatio-temporal scales examined (Beillouin et al. 2021). In this thesis, I work with the mono—strip—pixel transition pathway, representative of a gradient of increasing in-field diversity resolution, to try to identify possible response relationships in the Dutch, organic, arable context (Fig. 1.4, theoretical lines). Linking these relationships to the final framing question—*what does it mean for management and technology?*—is approached qualitatively in this thesis.

In the following sections I elaborate on the specific objectives which are linked to the framing questions and describe how they are addressed in each part of the thesis.

1.5. Study objectives

The overarching objective of this research was to explore, test, and assess crop diversification methods on a complexity continuum, at a realistic field scale within a European industrial arable context, in order to better understand the capacity of these methods to deliver production and other agroecosystem services, and to understand the management implications of each method. Taking the arable field as the focus of study, I approached the main objective from four angles, which aimed to:

1. Gain a delimited overview of the research to date on AES delivery from diversification practices by focusing on the most used diversification method in Europe: incorporating legumes into crop rotations (Chapter 3);
2. Develop a conceptual framework for how to think about the options farmers have for diversifying their cropping systems and the relationship between these options and AES delivery (Chapter 4);
3. Field test a range of crop diversification practices from currently feasible to future-oriented, quantify AES delivery in these systems, and relate AES responses to diversity resolution (Chapters 4 + 5);
4. Untangle the technological challenge of designing the management support tools needed to facilitate a move towards more complex cropping systems in the future, and thereby entangle the challenge with social and practical questions (Chapter 6).

1.6. Thesis structure and research methods

I approached the four research angles by employing a variety of methods; these include literature review, development of heuristic tools, agroecological field trials, and interactive design projects with diverse stakeholders. Methods are described briefly in the following paragraphs and in detail in each relevant chapter. Figure 1.5 provides a graphical overview of the approach and contents of each chapter, and how they relate to each other and the conceptual framing of looking to the past, present and future.

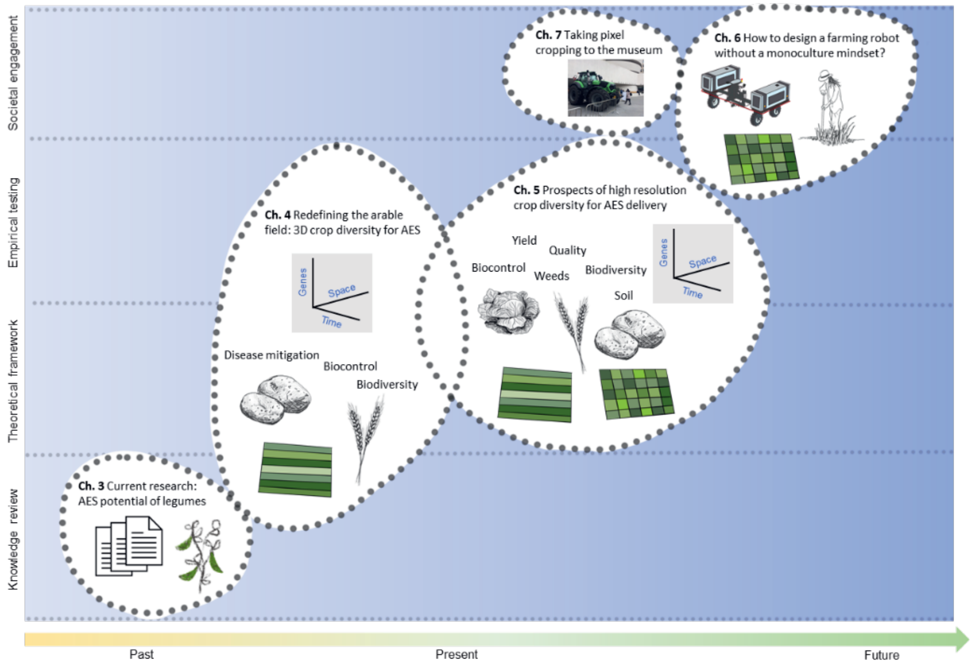

Figure 1.5. Graphical overview of the thesis chapters—their approach and contents.

Before presenting the research chapters, I first offer an ABCs of the thesis (Chapter 2) which highlights key terms relevant to understanding the content of the thesis. The aims of the chapter are to provide a supplement for readers coming from different disciplinary backgrounds and to provide transparency on the multiple genres of disciplinary 'jargon' one might encounter in the thesis.

I then begin the research content (Chapter 3) by looking to the past with a review of the state of the art in agricultural research regarding AES monitoring in European crop diversity experiments. Here we present a systematic literature review focusing on the most practiced diversification method—incorporating legumes into crop rotations—and identify the least and most studied legume inclusion methods and reported-on AES. We use descriptive statistics to analyze the reviewed literature and discuss the likely reasons for what we found to be a very narrow scope of legume-related crop diversity research in Europe. The findings of the review provide direction for the study presented in the next chapter, which investigates the diversification method and AES we found to be least reported on in the literature: strip cropping and pest and disease control.

In Chapter 4 we turn to the present. Upon beginning the research for this chapter, we discovered that a robust conceptual framework for understanding the effects of diversification practices on agroecological performance metrics was sorely lacking from the literature. Chapter 4 thus begins by introducing a novel heuristic framework developed for conceptualizing and visualizing diversity as 'three-dimensional', composed of the axes *time*, *space*, and *genes*. We then use the framework as a conceptual basis for analyzing empirical data from two long-term strip cropping field studies located in Lelystad and Wageningen, both in the Netherlands, where we look at the effect of crop diversification methods at various resolutions on pest and disease control in organic wheat and potato cropping systems. The findings of Chapter 4 highlight the importance of gaining further insights into how far down the complexity continuum the benefits of a particular diversity dimension extend, and under what conditions higher resolutions of diversity—and the associated burden of management for farmers—may be warranted to achieve sustainability aims. The next chapter then sets out to investigate what the optimal resolution of diversity might be in the Dutch context.

In Chapter 5 we utilize three years of empirical data which were collected in a long-term organic crop diversification experiment in Wageningen, the Netherlands. The experiment tested a range of diversification practices that included both currently feasible options (strip cropping of various kinds) and future-oriented (pixel cropping) techniques and which spanned a continuum from less to more complex. At the field experiment we measured a range of AES indicators selected to capture both common agronomic measures of success and which address research gaps identified in the review in Chapter 3. These were: soil fertility, crop productivity, weed control and diversity, and biocontrol potential. To analyze the field data, we first extend the functionality of the three-dimensional diversity heuristic presented in Chapter 4 by devising a novel system for calculating scores for each diversity dimension. This extension allows the heuristic to be used as a quantitative tool which we then apply to the empirical field data, using the diversity scores calculated for each of the tested diversification practices as predictor variables in the statistical analyses.

Both the quantitative findings of Chapter 5 and the qualitative learning gained from the multiple years of working with the experimental practices in the field point to the importance of practical field-level management in successfully approaching production and AES aims. While agroecological theories continue to point to the potential of diverse cropping systems, the results for the pixel cropping trial presented in Chapter 5 indicate that there may be an inherent limit to this potential, imposed by a lack of appropriate technologies which could facilitate optimal management.

In Chapter 6 we delve into to the question of technology in agrobiodiverse cropping systems, asking whether automation could be a productive option for avoiding a management tipping point in systems more structurally diverse than strip cropping. We take pixel cropping as a case study for addressing this question, approaching it as a proxy for a wider range of agroecological modes of farming. In this chapter we engage the method of "research through design" as described by Prost (2021), and draw on a series of discussion groups, workshops, design challenges, and interviews held in and around the Wageningen pixel cropping field trial. We bring together the findings of these happenings with historical trends and socio-technical discourse to assess the potential of robots to meet the multifaceted management demands of highly diverse cropping systems.

Chapter 7 offers an interlude between the research chapters and the final synthesis. Here I introduce the exhibition *Countryside, the Future*, a project which brought my pixel cropping research to the Solomon R. Guggenheim Museum in New York in 2020. I was a key contributor to the exhibition and engaging in the project was pivotal in how I developed my thinking about the thesis research and its potential impact for society. Chapter 7 presents a snapshot of the process and outcomes that framed my engagement, offering first a reflection on what the museum project offered to the thesis research overall and then a visual essay showing the narrative of competing agro-futures within which pixel cropping was positioned, as it was displayed in the museum.

In the final chapter, Chapter 8, I braid together the key learnings from each thread of the research. I draw connections between elements of the literature review, agroecological field study, conceptual framework for diversity, and design processes in an effort at providing a transdisciplinary synthesis of the research and the ways in which it addresses (or not) the questions and objectives outlined in sections 1.4 and 1.5. I conclude by identifying further directions for which to take the work and to expand the breadth and depth of crop diversity research towards realizing diversified industrial cropping systems in the future.

Chapter 2

ABCs of the thesis

In this thesis I have woven together concepts and methods from multiple disciplines into a single braid exploring a pathway towards diversified industrial-scale cropping systems. In doing so I make use of terminology, characters, and narratives from a transdisciplinary toolbox. To aid readers transiting over from various disciplines, I offer an ABCs of the thesis. It is not meant to be a comprehensive glossary, rather to highlight key terms which appear directly in the text and/or play an inherent role in the framing of the research. The format is inspired by the publication The ABCs of Art, Botany, and Cultivation (Cluitmans, 2021).

A

Agrobiodiversity	The planned and associated floral and faunal biodiversity of agricultural ecosystems (see also *Biodiversity*).
Agroecology	Farming practices and scientific approach which draws on natural processes as the foundation of sustainable farming. Also refers to a cultural and political movement encompassing peasant farmers' fight for food justice, food and seed sovereignty, and social equity. See FAO (2018); Francis et al. (2003); Méndez et al. (2013); Nicholls and Altieri (2018); Timmermann and Félix (2015); Wezel et al. (2009).
Agro-futures	A plurality of ways that the future of farming is envisioned—how it will look, how it will function, what it will produce, where it will be located, what scale it will occupy, who or what will manage it, etc. (see e.g. *Half Earth / Sharing the Planet*).
Arable agriculture	Cultivation of broad-acre crops, outdoors, on soil. Can include cereals, oil crops, root and tuber crops, and vegetables grown on a large scale. Does not include market gardening, poly tunnels, or indoor forms of horticulture.
Arthropod	Invertebrate animal of the phylum Arthropoda, having an exoskeleton, a segmented body, and jointed appendages.
Assemblage	A collection or gathering made of things and/or beings; a whole made up of pieces fitted together. "Assemblages are open-ended gatherings. They allow us to ask about communal effects without assuming them" (Tsing 2015, p. 22-23).

B

Biocontrol	The control of crop pests by natural predators, e.g. aphid populations controlled by predation by ladybeetles or weed seeds predated on by ground beetles.
Biodiversity	A measure of the variation of all life on earth, from genetic to species to ecosystem level. Coined by E. O. Wilson in the 1980s, the term combines *biological* and *diversity*.
Braid	To weave together multiple individual strands or threads into a single unit, in which the strands remain identifiable but also become part of an emergent unified whole.

C

Complexity	The web of relations that emerge from (planned) heterogeneity, e.g. an assemblage.
Countryside, the Future	An exhibition of research presented by Rem Koolhaas, Samir Bantal / AMO and many collaborators, which occupied the Solomon R. Guggenheim Museum in New York, New York February 2020-February 2021. The exhibition explored “radical changes in the rural, remote, and wild territories collectively identified as “countryside,” or the 98% of the Earth’s surface not occupied by cities.” (www.guggenheim.org/exhibition/countryside)
Clock of the Long Now	A clock designed by Danny Hillis and Steward Brand to keep perfect time with minimal maintenance for at least 10,000 years.
Crop rotation	Growing a different crop in the same field from year to year in a (predetermined) sequence of multiple years. In the Netherlands, organic farmers typically follow a six-year crop rotation, e.g. cabbage—barley—potato—wheat—pumpkin—grass-clover.

D

Dimensions of diversity	Three ways in which heterogeneity can be introduced to monocultural cropping systems: in time, in space, and in genes.

E

Ecofeminism(s)	Branch(es) of feminism which look at the intersection between gender, environmental degradation, and social injustice. Broadly positions patriarchal values as aggravators of the nature/culture disconnect, resulting in disproportionate damage to marginalized people and communities. See Gaard and Gruen (1993), Estévez-Saá and Lorenzo-Modia (2018).
Ecomodernism	The attitude or position that technology can be used to enhance the quality of human life and advance economic growth without increasing environmental impacts (see also *Techno-fix; Wizard and Prophet*).
Ecosystem services	Services (economic, aesthetic, health benefits) provided to humans by biodiversity and the functioning of natural ecosystem processes. Agroecosystem services (AES) refers to the services provided to humans by the biodiversity and functioning of agricultural ecosystems.
Epigeic	Describes an organism who dwells on the soil surface.
Ethos	A particular way of defining the elements, objects, and subjects the world is made up of; also a mood, an aesthetic, a way of narrating, and a collectively shared attitude (following van Dooren and Rose (2016)).

F

Field	An area of land used for farming; a geographical management unit which shapes how a farmer conceptualizes and executes cultivation activities.

Farm Hack	An international community of farmers who build and modify their own tools. Designs and building plans are freely shared, online (www.farmhack.org) and at in-person meetups.

G

Global North	A delineation of northern global geographies, as opposed to southern. The term is employed to distinguish between both the pedoclimatic characteristics of the northern vs. southern hemispheres and to make a distinction on the basis of broad socio-cultural differences between the regions, e.g. economic wealth, level of ‘development,’ and industrialization status. An alternative classification can be made on the basis of economic wealth and power rather than geography, delineating the global minority (wealthy, powerful nations) and the global majority (the rest of the world).
Green Revolution	A period of agricultural innovation beginning in the late 1950s, characterized by efforts to increase the yields of staple crops produced globally. The approach centered crop breeding (replacing traditional, indigenous, and landrace varieties with ‘improved’ crops bred and genetically engineered to yield more), agrochemical inputs (e.g. synthetic fertilizers, pesticides, and herbicides), and intensification of specialized cropping systems.
Ground beetle	A large classification of arthropods in the family Carabidae. Important predators in agricultural settings, known to prey on a variety of crop pests (eggs, larvae, adults) and weed seeds.

H

Half Earth / Sharing the Planet	Two narratives envisioning two different nature futures, each presenting an alternative conservation scenario to address the global biodiversity crisis, climate change, and food security. In the Half Earth vision, nature is separated from human activities; half of the earth is set aside for conservation purposes with minimal or no human intervention, and

		agriculture is intensified elsewhere with the aid of technological innovation. In the Sharing the Planet vision, humans and nature coexist in the same spaces; human and nature systems are integrated into working landscapes where agriculture is interwoven with nature via agroecological practices, ecological intensification, and green infrastructure. See Immovilli and Kok (2020).
	Harvestmen	Organisms of the order Opiliones, class Arachnida, phylum Arthropoda. Generalist predators and natural enemies of some crop pests, e.g. aphids.
I	*The Impossible*	A sailing vessel invoked by René Daumal in his novel Mount Analogue (1959). *The Impossible* takes its passengers on a journey to locate and climb Mount Analogue, a mythological locale that may or may not exist outside of the seekers' minds.
	Industrial cropping systems	Crop production systems which are characterized by high levels of mechanization, intensive production capacities, strong dependence on external inputs (agrochemicals in conventional systems), and high levels of specialization.
	Intercropping	Used to describe a range of cultivation practices in which two or more crop species or genotypes are coexisting in the same field at the same time for at least part of the growing season (e.g. crop mixtures, row intercropping, multi-row intercropping (strip cropping, pixel cropping), syntropic farming, etc.).
J	Jejune	Simplistic, superficial, artless, boring. The disparaging term used by Robert Smithson in his essay "A Sedimentation of the Mind: Earth Projects," to describe the tradition in English gardening whereby designers would aspire to create "ideal nature" in the form of "tranquil" and

		“banal” Edens (Smithson 1968). A term relevant for describing the ‘Earth project’ that is industrial monoculture farming.
K	Kilogram	The base unit of weight used in the International System of Units (SI), equal to 1000 grams or 2.2046 pounds.
L	Labor	Physical or cognitive work. In a farming context, usually refers to the physical work of doing daily cultivation tasks, e.g. soil preparation, sowing, weeding, harvesting, etc.
	Legume	A plant in the family Fabaceae. Includes peas, beans, lupins, clovers, lentils, and other pulses. Legumes are valued in agricultural systems for having a symbiotic relationship with nitrogen-fixing bacteria which are hosted in legume root nodules.
M	Monoculture	The cultivation of a sole crop of a sole genotype in a single field unit. May also refer to the repeated practice of growing a sole crop in the same field unit from season to season (e.g. a continuous wheat ‘rotation’).
N	Naturecultures	A concept that approaches nature and culture as so entangled that they cannot be separated; rejects the ontological divide between nature and culture, human and non-human. Introduced by feminist scholar Donna Haraway.
	Nature-inclusive agriculture	A phrase commonly used in agricultural policy dialogue, referring to practices which allow for the co-existence of nature and farming. May be defined as: a form of agriculture that goes “hand-in-hand with biodiversity”, agriculture that “produces food within the boundaries of nature”, “agriculture that considers nature as a partner” or agriculture that “makes optimal use of the natural environment and integrates it into the business operations” (Erisman et al. 2017). Manifestations

	commonly include the addition green infrastructure on the farm, e.g. flower strips or hedgerows between (monocultural) crop fields.
Natural enemy	A natural predator of an organism considered a pest in an agricultural system. E.g., a parasitoid wasp who lays its eggs in *Pieris brassicae* larvae (a cabbage-feeding herbivore) or harvestmen who eat aphids.

O

Ontological turn	Broadly, the development of multiple philosophical lines of theory which focus on being. Characterized by how they "collapse a number of dualisms underlying many theories in sociology, including agency/structure, nature/culture, animate/inanimate, reason/emotion, mind/matter" (Darnhofer 2021b).
Orthogonal	Of or involving right angles; implies straight lines.

P

Phytophthora infestans	A water mold; the cause of potato late blight, a disease that infects potato leaves and stems, causing above-ground biomass to die off and tubers to rot. Responsible for the European and Irish potato famines in the 1840s.
Pixel	In digital imaging vocabulary, the smallest controllable unit on the computer screen. In farming, can refer to the smallest unit of management in the field (see *Pixel cropping*).
Pixel cropping	An open-field cultivation method in which many different food and service crops are planted together in diverse assemblages made up of small (0.25 m^2 – 2.25 m^2), square crop patches ('pixels') arranged in a grid. Within the pixels multiple agroecological techniques are employed to increase temporal, spatial, and genetic in-field diversity (rotation, intercropping, crop mixtures),

		conserve soil (continuous cover, green manures), and facilitate biological pest control (habitat and resource contiguity and continuity).
	Polyculture	The cultivation of multiple crop species and/or varieties in a single field unit; the opposite of monoculture.
	Prospero the Robot Farmer	A prototype farming robot created by David Dorhout, founder of Arcadia Tractor Corp. Prospero walks on six legs and is designed to monitor soil conditions and select and plant crop seeds based on these conditions. Dorhout's inspiration in building Prospero was to provide a catalyst for thinking about alternative farming futures, saying that he wanted people to consider that perhaps "the boundaries aren't bigger and bigger equipment. Maybe small independent agents are where the future is" (Dorhout 2020).
Q	Queer ecology	An "interdisciplinary constellation of practices that aim, in different ways, to disrupt prevailing heterosexist discursive and institutional articulations of sexuality and nature" (Sandilands 2016, p. 1). Queer ecological scholarship has "attempted to develop theoretical and activist connections between sexual and ecological politics, often drawing from ecofeminist and environmental justice perspectives and including concerted attention to the racialized, gendered, colonial, and species politics with which notions of sex and nature are articulated" (Sandilands 2016, p. 2).
R	Redefine	To establish a new definition of.

Response-ability	The ability to respond to the world (and its changes, challenges, and entanglements) with deliberation and care: “response-ability invites people to recognize their abilities to change their actions or intentions when something previously unknown or new emerges within a set of relations” (Burch and Legun 2021, p. 148). Delineated from responsibility, which holds the connotation of obligation rather than agency. See also Barad (2007).
Resolution	The number of units contained in a display (see *Pixel*). Higher resolution equates to smaller units. Originates in the context of computer screens, where a higher resolution translates into a sharper image.
Richness	A measure of biodiversity; the number of taxonomic groups in a community or sample, e.g. species richness.
Robot	Tentatively defined here as a “perceptible programable machine” following Bechar and Vigneault (2017).
Rove beetle	Arthropods of the family Staphylinidae, characterized by a largely exposed abdomen. Commonly omnivorous, known to prey on the eggs and larvae of crop pests such as moths, springtails, and aphids.

S

Shannon Index	A measure of biodiversity which accounts for both the richness (see *Richness*) and the relative abundance of taxonomic groups in a community or sample (Spellerberg and Fedor 2003).
Spider	An eight-legged arthropod of the class Arachnida. Spiders are generalist predators and prey on crop pests including thrips, aphids, and moth larvae.

Strip cropping	The practice of growing two or more different field crops in alternating adjacent, narrow, multi-row strips which are wide enough to cultivate independently with machinery but narrow enough to facilitate ecological interaction between crops.

T

Techno-fix	The response that technology, rather than fundamental changes in human behavior, can fix any problem. Used here to refer specifically to responses to environmental and agricultural sustainability problems.
Three Sisters	An indigenous farming practice in which three crops—corn, beans, and squash—are sown together in the field. The spatial arrangement and functional behavior of the three species encourages interspecies facilitation, complementarity, niche differentiation, and resource sharing which enhances the overall growth of the crop, and the harvested produce provides a nutritious diet to people. The practice is thought to have originated in Mesoamerica several thousand years ago. A variation still practiced in Central America today is known as *milpa*.
Turing pattern	A concept developed by mathematician Alan Turing to describe how patterns form in nature through the self-organization of cells and organisms. Examples include vegetation growth and camouflage markings on fish or mollusks.

U

Urbanism for vegetation	A phrase the architect Rem Koolhaas used to understand pixel cropping as an antithesis to monoculture (see Ditzler 2020, p. 302).

V

Vertical farming	The cultivation of crops in buildings, in vertical arrangements of plant beds stacked on top of each other.

W	Weed	A plant growing in a place where humans do not want it to grow. In agriculture sometimes referred to as ‘arable flora’. For many farmers, controlling weeds is the cultivation activity that consumes the most time and energy, because weeds are perceived as detrimental to crop production.
	Whole Earth Catalog	A periodical published in the USA by Stewart Brand and colleagues, which ran from 1968-1972 (with a few later editions). The *Catalog* featured product reviews and sourcing information for self-sufficient lifestyles and do-it-yourself projects, as well as essays and book reviews by counterculture thinkers on themes of ecology, technology, and holism.
	Wizard and Prophet	An allegorical tale used by the author Charles Mann (2018) to describe “dueling visions” for the future of Earth. The Wizard represents a technology-driven vision in which human ingenuity, e.g. through the manipulation of natural processes, will solve all environmental crises (see also *Ecomodernism, Techno-fix*). The Prophet represents a stance in which nature is seen as finite and should be preserved by humans changing their consumption behavior rather than a techno-fix.
X	Xenophobia	Fear or hatred of that which is perceived to be foreign or strange. I have used this term to describe the effects of crop breeding targeted to monocultural production environments, e.g. the behavior of cabbage plants in a pixel plot which appear to yield better when surrounded by other cabbage neighbors and grow poorly when neighbored by non-kin.
Y	Yield	A measure of the productivity of a crop, generally referring to the quantity of harvested crop product per unit of land area. In this thesis crop yields are expressed in kilograms per square meter or tons (1000 kilograms) per hectare (see also *Kilogram*).

Z

Zome	A building constructed using unusual geometry, credited to designers Steve and Holly Baer; inspired by Buckminster Fuller’s geodesic dome. A redefinition of what home could look like. Zomes were designed to respond to their environment and to be powered by solar energy. Drop City, a counterculture commune built in Colorado, USA in the 1960s, featured several zomes and its residents were among the target audience of the *Whole Earth Catalog*.

Chapter 3

Current research on the ecosystem service potential of legume inclusive cropping systems in Europe. A review

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Abstract

Legume crops hold promise to diversify the currently simplified rotations that dominate Europe and to increase the sustainability of European farming systems. Nevertheless, most legumes have been ignored by farmers, advisors, and value chain agents in the EU, where legumes are estimated to occupy only ~2% of arable land. Recent surveys find that farmers see a lack of knowledge on the agroecological impacts of (re)introducing legumes as a key barrier to legume adoption. A review of current research on the agroecological potential of legume-inclusive cropping systems would help in assessing whether research targeting sufficiently supports farmers in overcoming this barrier.

We have systematically reviewed and synthesized published literature reporting on agricultural ecosystem service delivery in European cropping systems with legumes included compared to those without legumes. Our analysis of 163 published articles revealed: 1) The bulk of published research addresses production-related services delivered by few legume species (pea, clover, faba bean, and vetch, 70% of reviewed studies) comparatively assessed in cereal-based rotations; 2) Substantial knowledge gaps also exist, encompassing ecosystem services with less direct relevance to economic outcomes (e.g. biodiversity) and with potential for high variability (e.g. pest and disease suppression); 3) Studies at plot-level and within-season scales dominate (92% and 75% of reviewed studies, respectively). Assessed in the context of recent complementary studies, we find that a limited research focus is both counter to knowledge demands from farmers and likely the result of self-reinforcing socio-technical regimes which prioritize production over non- or indirectly-marketable ecosystem services. We conclude that scientists in Europe should diversify research to include legume species, ecosystem services, contexts, and scales not yet well studied, in order to provide the agroecological knowledge base farmers need to amplify the potential benefits of crop diversity.

Keywords: Crop diversification; research targeting; technological regime; socio-technical lock-in; knowledge development.

3.1. Introduction

Diversification in industrialized arable farming is increasingly recognized as necessary to mitigate the negative externalities caused by low-diversity cropping systems (IPES-Food 2016). In the European Union (EU), cereals, maize (grain and silage), oilseed rape, and sunflower together cover 92% of the arable land area, resulting in short rotations (3-4 years on conventional farms) dominated by cereals, maize, and rapeseed in the north, and maize and sunflower in the south (Eurostat 2019; Mudgal et al. 2010). Introducing legumes into sole-crop stands and simplified rotations is one of the most commonly used diversification measures researched in cropping systems experiments globally (Hufnagel et al. 2020), as legumes are considered to afford many social and ecological benefits (Voisin et al. 2014; Zander et al. 2016). In Europe, societal interest in the potential of legumes has grown amidst discussion of the so-called 'protein transition' (Aiking and de Boer 2018) and the rise of sustainability-based legislative initiatives which seek to reduce reliance on agrochemical inputs and increase agrobiodiversity (e.g. the EU Green Deal's 'Farm to Fork strategy') (European Commission 2020).

The potential benefits of increasing legume production in the EU by (re)introducing them to current cropping systems span from field to consumer. These benefits can be summarily described as ecosystem services (ES), defined as services people obtain from the functioning of ecosystems which support life on Earth (MEA 2005). ES provided by production ecosystems (agro-ecosystem services) (Zhang et al. 2007) are related to both biological and agronomic aspects. At the field level, including legumes in cropping systems (grown as food, feed/fodder, forage, or service crops) is beneficial from an agronomic perspective because they bring nitrogen (N) into the soil through symbiotic N fixation, thereby reducing the need for N fertilizers in companion or following crops (Peoples et al. 2009), improving the use of soil N resources (Jensen et al. 2020), and in some cases improving the yields of following crops (Angus et al. 2015). Aggregated at farm and landscape levels, increased presence of legumes in European cropping systems would cascade benefits through regulating ES such as nutrient cycling, potentially reduced greenhouse gas emissions, and biodiversity conservation (Watson et al. 2017). In mixed crop—livestock systems, production of legumes as feed and forage has been shown to reduce mineral N fertilizer use and nitrous oxide emissions (Reckling et al. 2016), and feed and forage self-sufficiency through on-farm legume production would improve the circularity of farming systems (Koppelmäki et al. 2021). Increasing production and consumption of legumes is also beneficial from a consumer perspective, as legumes provide high quality proteins, which are an important component of a healthy diet (Weindl et al. 2020; Willett et al. 2019). Fulfilling a larger portion of human dietary protein needs with legumes in place of meat would contribute to more sustainable diets by reducing the demand for livestock production and its associated environmental impacts (Springmann et al. 2018; Willett et al. 2019).

Despite these apparent benefits, the area of farmland under legume production in the EU is currently estimated at only ~ 2% of total arable land (Kezeya Sepngang et al. 2020; Pelzer et al. 2017). After a steady decline for several decades, the area started to increase marginally after

2014 when greening measures were introduced in the EU's Common Agricultural Policy, however gains are regionally variable and can be largely attributed to an increase in the production of soybean (FAOSTAT 2018; Kezeya Sepngang et al. 2020; Schreuder and de Visser 2014). These trends appear to indicate that various interacting factors, referred to as socio-technical lock-ins, are dissuading farmers from including legumes in cropping systems (Magrini et al. 2016; Meynard et al. 2018). A review on the topic pointed to the dominance of economic systems that favor specialization over diversification, and the failure of markets to promote legumes, as the main barriers to legume adoption in Europe (Zander et al. 2016). Moreover, grain legumes often present more unstable yields compared to autumn-sown cereals (Reckling et al. 2018), and how (or whether) they fit into current systems is context dependent (Reckling et al. 2020).

In spite of these challenges, a recent study in France found that some farms are transitioning towards including more legumes (Mawois et al. 2019). Importantly, this study showed that in addition to market opportunities and supportive policies, a key factor driving the stable introduction of legumes on farms was increased knowledge and awareness of their multiple and long-term agroecological benefits, i.e. the ES that they can deliver. Similarly, a comprehensive study on barriers to crop diversification in general found that "convincing" conventional farmers in Europe to adopt more agroecological practices, such as including legumes in rotations, would require providing them with more evidence of the positive relationship between crop diversification and the sustainability of their farms (Morel et al. 2020). Additionally, Zimmer et al. (2015) surveyed Luxembourgish farmers and found the majority to be under-informed about legume cultivation. These findings highlight the importance of directing research priorities to effectively contribute agroecological knowledge in support of crop diversification in general and of legume uptake specifically.

Mutually reinforcing feedback loops between research trends and technology adoption in agricultural systems have been identified in previous studies (Vanloqueren and Baret 2009), implying that research on ES delivery conducted at field and farm levels (as part of a multifactorial approach that includes market and policy foci) has an important role to play in un-locking barriers to legume adoption. Currently, a cluster of research projects focusing on crop diversification in the EU's Horizon 2020 funding scheme (www.cropdiversification.eu) is working to put a spotlight on legume research and fortify the knowledge base needed to support EU farmers in expanding the area of legume-inclusive cropping systems. Among market-based and socio-technical themes, several partners in these projects investigate the ecosystem (dis)services gained by introducing legumes in rotations as food, feed/fodder, forage, and service crops (Fig. 3.1). As is often the case in such projects, the topics chosen for study (e.g. which ES, from which legume species, and through which inclusion method(s)) may have been influenced by existing lines of research and prevailing analytical capabilities. The concentration of resources in projects like those in the crop diversification cluster constitutes a major opportunity for research on ES delivery to support legume adoption in practice (Mawois et al. 2019; Morel et al. 2020). However, it is important to critically reflect on whether studies like these will actually provide the agroecological knowledge needed for the development of on-farm practices or if a re-focusing of research agendas may be necessary.

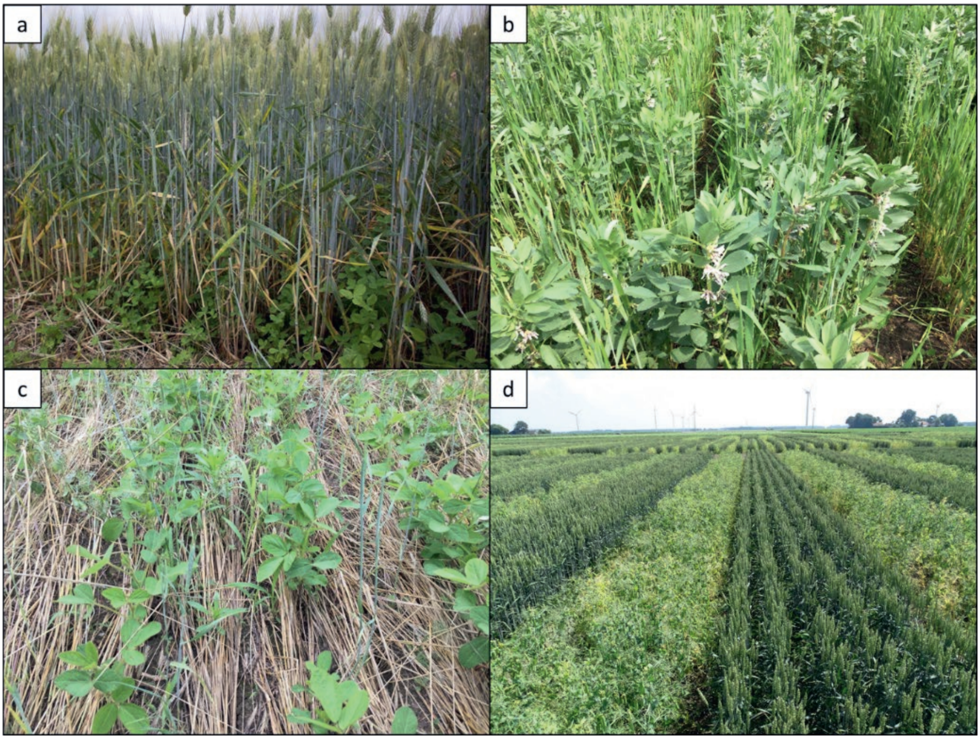

Figure 3.1. Some options to include legumes in European arable cropping systems being studied in the Horizon 2020 crop diversification cluster: **a**) durum wheat under-sown with clover in the SSSA-IWMPRAISE experiment at CiRAA, Pisa, IT; **b**) winter wheat and faba bean mixed cropping in the DiverIMPACTS / LegValue field experiment at Wageningen, NL; **c**) soybean sod-seeded on rye dead mulch in the LegValue experiment at CiRAA, Pisa, IT; **d**) strip intercropping of pea with wheat in the REMIX experiment at Wageningen, NL. Photos **a** and **c** by Daniele Antichi, photo **b** by Lenora Ditzler, photo **d** by Dirk van Apeldoorn.

Essential for developing pertinent research agendas would be a comprehensive overview of what ES have already been studied, for which legume species, in which cropping systems, and where. Such an overview would provide a lens through which to sharpen current research efforts to ensure that relevant and timely knowledge is being pursued. While a growing body of scientific literature has documented the ES delivered by legume species in cropping systems, no systematic reviews of the research subjects, i.e. the systems and ES studied, have yet been conducted. Stagnari et al. (2017) and Watson et al. (2017) both provided relevant and general qualitative overviews, but in the form of narrative reviews. Systematic reviews have been conducted for certain legume species (e.g. faba bean (Vicia faba L.), Köpke and Nemecek 2010) and for certain ES (e.g. biocontrol of pests, Iverson et al. 2014; and soil microbial activity, Duchene et al. 2017), but neither address multiple ES nor comprehensively inventory legume-inclusion systems to reveal the areas afforded attention by the research community.

In this study we aimed to systematically identify the current areas of knowledge abundance and scarcity, as related to ES research in European legume-inclusive cropping systems. We addressed this aim by conducting a synthetic review of peer-reviewed scientific literature reporting on ES delivered by the inclusion of legumes in existing European agro-ecosystems. Based on the results, we sought to identify the most consequential knowledge gaps that should inform current and future legume-based research initiatives. Given the present spotlight on legumes in EU research and agricultural policy, we focused the review on studies conducted in Europe (EU28 countries, Norway, and Switzerland). Observing a general rise of ES research in agro-ecosystems around the globe, we expect that the highlighted trends and knowledge gaps will inspire reflection on research agendas even beyond Europe.

3.2. Review framework

This review was designed to illuminate trends in published, peer-reviewed research on the practices and functioning of legume agro-ecosystems, as we considered this knowledge an important contributor to breaking down barriers to legume adoption in the EU (Fig. 3.2). We looked specifically at studies in which ES delivery in systems with legumes included was compared to ES delivery in reference systems without legumes. We posit that such comparisons, which indicate the performance of comparable systems with and without legumes and show the effects of various options for diversifying current rotations, are highly relevant for farmers enacting incremental changes as part of a transition towards greater sustainability (Hill and MacRae 1996). Our review involved i) a systematic search for peer-reviewed published articles examining ES delivery in legume-inclusive European cropping systems compared to reference systems without legumes; ii) extracting meta-data from these articles to create a database and subsequent synthesis of the current research landscape showing what has been studied, where, and for which legume species, crop combinations, and management practices; and iii) confronting results with those from inventories of farmer needs for including legumes in their farming systems.

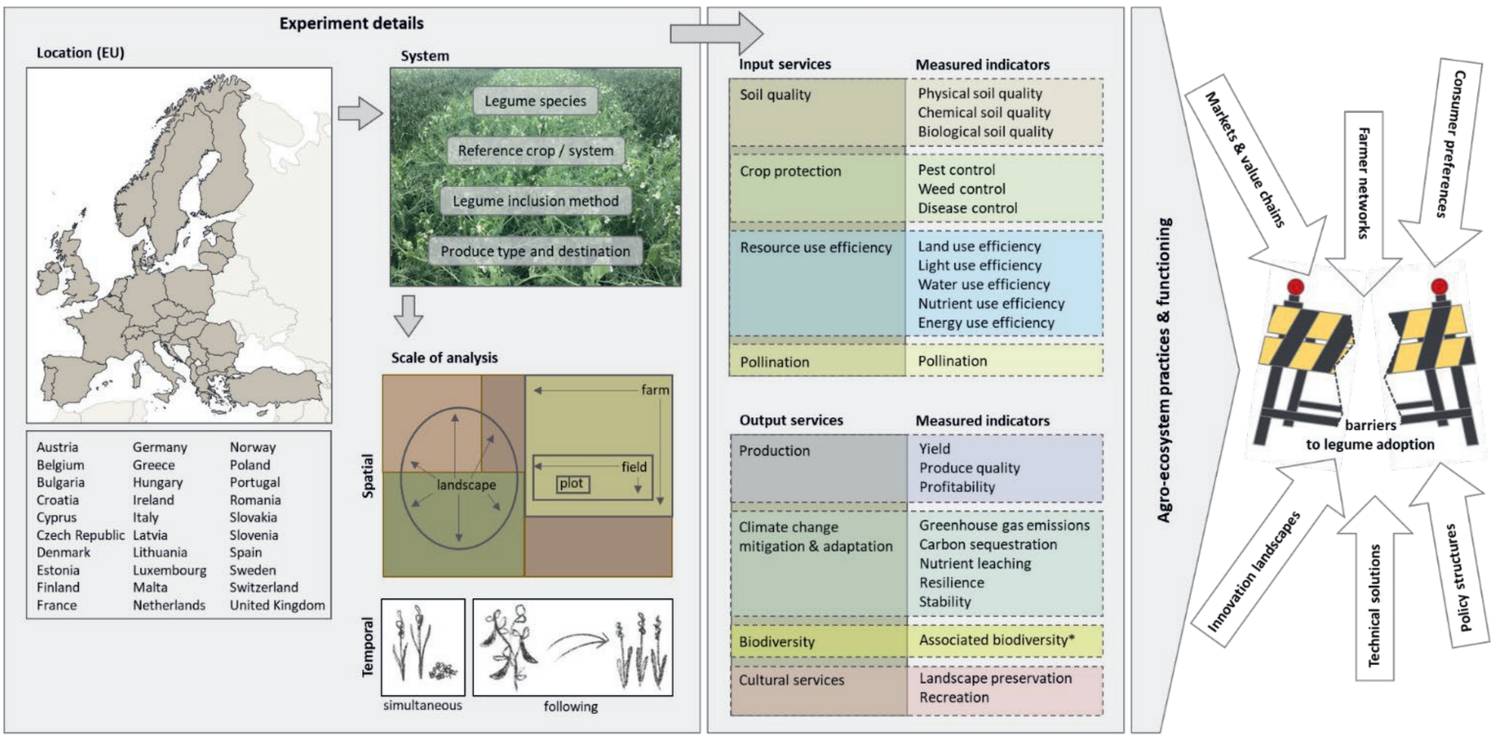

Figure 3.2. The subject of the research covered in this literature review comprises knowledge about the practices and functioning of agro-ecosystems including legumes compared to reference agro-ecosystems without legumes (content within the grey boxes). This agroecological knowledge is one factor contributing to a larger body of research topics and knowledge-generation activities needed to break down the barriers inhibiting European farmers from adopting legume crops specifically and diversifying cropping systems generally (white arrows at far right of the diagram, based on the findings of Magrini et al. (2016), Meynard et al. (2018), Mawois et al. (2019), and Morel et al. (2020)). *Associated biodiversity refers to unplanned biodiversity that is an outcome of the system and not implemented by the farmer; we thus consider it here as an output service, although others have classified it as an input service (Duru et al. 2015b).

We conducted a systematic literature search in Scopus and tracked the results following the Prisma reporting method (Moher et al. 2009). We combined four search term clauses using Boolean operators arranged in the following Scopus-compatible structure: TITLE-ABS-KEY((general agriculture terms) AND (legume inclusion method terms) AND (ecosystem service terms) AND (legume terms)). A complete list of the search terms included in each clause is provided in Appendix A3.1. For the purpose of the search, we defined ES following Duru et al. (2015b) as services (agronomic, ecological, economic, or cultural) which contribute to (input services, relevant to the farmer) or are generated by (output services, relevant to society) agricultural production practices. We considered ES to encompass disservices as well as beneficial services (Zhang et al. 2007). Drawing on existing reviews of ES derived from crop diversification practices (e.g. Kremen and Miles 2012) we inserted search terms in the clause 'ecosystem service terms' to cover the scope of ES expected to be associated with the inclusion of legumes in European cropping systems (Fig. 3.2). The search encompassed literature published up to and including December 31, 2019.

The full set of returned documents (>10,000) was first refined in Scopus using the "limit to" feature for subject area (agricultural and biological sciences), document type (article, article in press), country (EU28 plus Norway and Switzerland), and language (English). Manual additions were made to the document database by cross-checking the reference lists of the most recently published reviews and meta-analyses on related topics. Next, documents were screened for inclusion by reviewing titles, keywords, and abstracts using EndNote software (version X8, Clarivate Analytics, 2018) on the basis of four inclusion criteria: i) the research was conducted in the EU28 or Norway or Switzerland, ii) the research involved a field experiment (on-station or on-farm, no pot trials), iii) an ES other than or in addition to yield was measured, and iv) the research compared a cropping system with legumes included to a reference system without legumes. Modelling studies (including lifecycle assessments), reviews, and meta-analyses were excluded.

Each article deemed eligible for inclusion was read in full, and meta-data were entered into a database. These meta-data, extracted per article, included year of publication, location of study, experimental factors (including crop(s) studied and management practice employed (Table 3.1)), reference crop or system, produce destination, spatial and temporal scales of analysis, and which ES were measured. If multiple studies (sites or experiments) were reported in a single article, each study was entered into the database separately. During the full reading phase, articles found to not meet the inclusion criteria were dropped from the database. The final database contained 163 articles (Appendix A3.2) and consisted of 468 discrete entries. Since the appearance of the first single document in 1988, the number of articles in the database steadily increased to a peak of 25 in 2018, and then dropped to 12 in 2019 (the last year reviewed). A link to a complete list of the reviewed literature (with citation details) is available in Appendix A3.3.

Table 3.1. Management practices (i.e. methods through which legumes are included in cropping systems) as classified for the literature database and their definitions.

Method	Definition
Cover crop	A crop grown between seasons to provide soil cover and/or catch nutrients
Green manure	A crop grown between or during cash crop seasons, the residues of which are incorporated into the soil with the purpose of improving soil quality
Mixed cropping	Sowing multiple species or cultivars in the same field at the same time, as a broadcast mixture with a given seeding ratio but random spatial arrangement
Rotation	Growing different crop species in the same field over the course of seasons or years in a deliberate sequence*
Row intercrop	Sowing two (or more) crop species in the same field at the same time in alternate rows
Strip intercrop	Sowing two (or more) crop species in the same field at the same time in multi-row strips wide enough to allow independent cultivation
Relay cropping	Intercropping of two crop species in which the second species is under-sown in the first at a later point in the growing season

* Rotation here includes ‘multiple cropping’ (multiple crops grown in the same field one after another in the same season)

We analyzed the meta-data using descriptive statistics (counts, frequencies, and associations between study locations, crop combinations, management practices, and ES measured) to illuminate trends and gaps in the literature. For the analysis we combined the meta-data categories ‘management practice’ and ‘produce destination’ to create an aggregated classification describing the legume crop functional type: food/feed (for human consumption or fed to animals, representing a general market orientation), forage (grazed in situ), or service (returned to the soil). Food and feed were combined because it was often difficult to discern for whose consumption the legume was being grown (humans or animals), given the experimental setting.

3.3. Areas of research abundance: reflection of the productivist paradigm?

Our review revealed that much of the published literature on ES from legumes introduced in EU cropping systems is concentrated around combinations of a relatively small number of legume species, management practices, and measured ES (Fig. 3.3). A large cluster of studies (70% of the total) is centered on four main legume species (pea (*Pisum sativum* L.), clovers (*Trifolium* spp.), faba bean (including broad bean and pigeon bean, *Vicia faba* L.), and common vetch (*Vicia sativa* L.)) and their delivery of production-related services primarily in cereal-based mixed and row intercrop systems, with experiments located in five main countries (France, Denmark, United Kingdom, Switzerland, and Italy; data not shown). Several grain legume species potentially important for sustainable human diets (lentil (*Lens culinaris* Medik.), chickpea (*Cicer arietinum* L.), lupin (*Lupinus* spp.) and soybean (*Glycine max* (L.) Merr.)) are notably not as well represented; together these comprise just over 7% of all studies in the database. We found only one study that used strip intercropping, suggesting that despite being a once-popular way to incorporate legumes into cropping systems in the United States (Francis et al. 1986), it apparently never gained popularity in the EU. The most commonly studied production-related services include productivity measures (yield, produce quality, land use efficiency), as well as ES linked to the N-fixation capacity of legumes (chemical soil quality and nutrient use efficiency), and weed suppression.

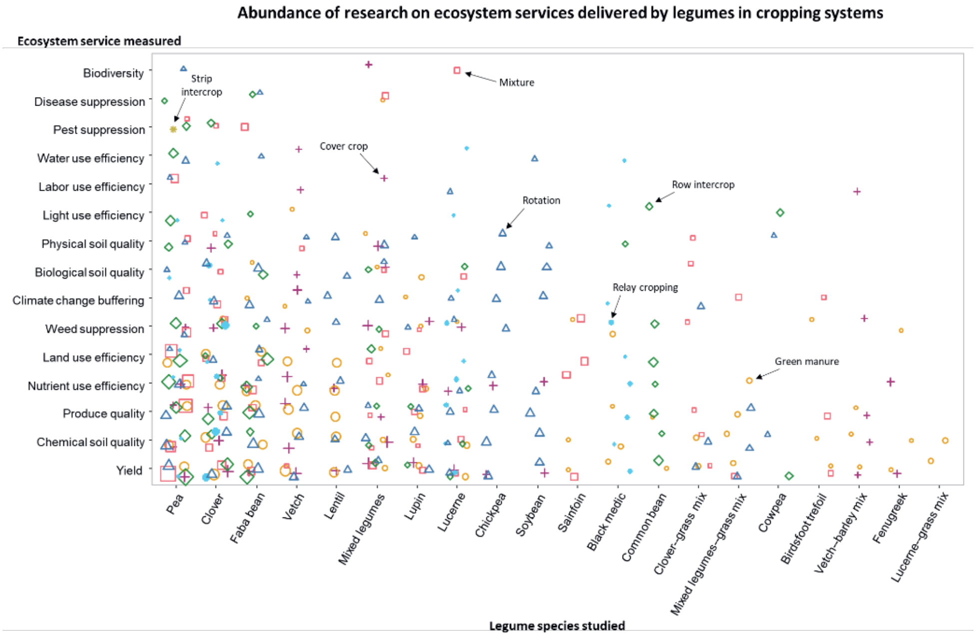

Figure 3.3. Matrix showing the number of synthesized peer-reviewed studies reporting on ecosystem services (*y* axis) delivered in cropping systems with different legume species included (*x* axis) compared to reference systems without legumes. Symbols and colors correspond to the legume inclusion method employed in the study. The larger the symbol, the more studies on that species–service combination; the largest symbol in the plot (*x* = Pea, *y* = Yield, inclusion method = Mixture) denotes 60 studies, and the smallest symbol (*x* = Pea, *y* = Pest suppression, inclusion method = Strip intercrop) denotes one study. Legume species and ecosystem services are ordered according to the frequency with which they appear in the literature review database.

These findings suggest that there is only a limited formal scientific basis for understanding the effect of legumes on ES delivery across the variety of locations, crops, and management practices possible in the EU. While more knowledge likely exists in other realms (e.g. grey literature, advisory service pamphlets, local-language reporting, etc.), the lack of peer-reviewed literature imposes an inherent limitation on efforts to support expansion of legume-inclusive cropping systems in Europe for policy makers and advisors relying on peer-reviewed scientific analyses. The focus we observe in the literature on production-related ES is logical: yield and produce quality have the most direct impacts on farmers' ability to market and make immediate revenue from the inclusion of legumes in cropping systems, so production-related ES gain high priority on research agendas aiming to provide support for farmers in adopting legume crops. This focus, however, is also likely reflective of the dominant productivist paradigm, which prioritizes market demands and thereby directs research to support such demands (Magrini et al. 2016; Zander et al. 2016), while deemphasizing other less-easily monetized benefits of legumes for farmers and society.

The influence of the productivist paradigm is further reflected in the fact that cereals are the companion or following reference crop against which the addition of legumes was studied in 69% of the total database entries. These studies are relatively equally distributed between those incorporating legumes as a service crop (often for facilitating a cash crop) and as a marketable food or feed crop. Studies using legumes as a service crop are dominated by those incorporating legumes as green manures or cover crops in a rotation with cereals, while those using legumes as a food or feed crop predominantly refer to systems where legumes and cereals were combined in rotations or intercropped by row or as mixtures (Fig. 3.4).

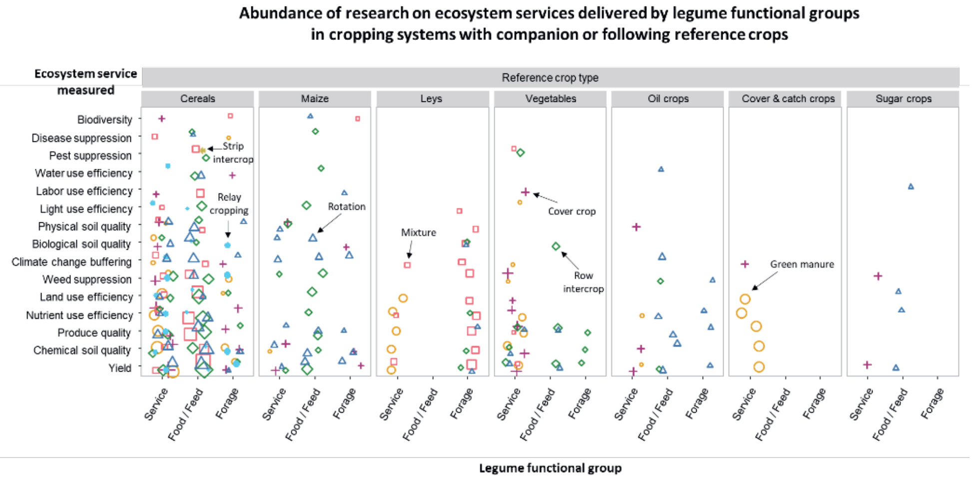

Figure 3.4. Matrix of associations studied in the reviewed literature between legume crop functional groups (service (returned to the soil), food/feed (for human consumption or fed to animals), forage (grazed in situ), *x* axis) and ecosystem services (*y* axis) delivered when introduced to systems with non-legume companion or following reference crop types. Symbols and colors correspond to the legume inclusion method employed in the study. The larger the symbol, the more studies on that combination; the largest symbol in the plot (group = Cereals, *x* = Food, *y* = Yield, inclusion method = Mixture) denotes 60 studies, and the smallest symbol (group = Cereals, *x* = Food, *y* = Pest suppression, inclusion method = Strip intercrop) denotes one study. Ecosystem services and reference crop type are ordered according to the frequency with which they appear in the literature review database.

Within the legume–cereal studies subset, three combinations make up 25% of the total: pea–barley (*Hordeum vulgare* L.), pea–wheat (*Triticum* spp.), and clover–wheat. Within these three groups, there appears to be specialization based on experiment location. Studies on pea–barley combinations are most frequent in Denmark, while pea–wheat and clover–wheat studies are more common in France (Fig. 3.5). Again, these studies focus primarily on production-related ES. Although many fewer legume–cereal studies report on the remaining range of ES, each ES is covered by at least one study in the reviewed database, with the exception of biodiversity for which there are no studies in this subset of the literature. For pea–wheat, we saw that the two crops were integrated into experimental systems most often as mixtures, and that yield, resource use efficiency (nutrients, land, and labor), produce quality, and chemical soil quality were the most commonly studied ES. Pea–barley was more often studied in row intercropped systems. Differing from pea–wheat, additional ES reported on for pea–barley include water and light use efficiency. Clover was commonly incorporated into wheat systems through temporal diversification, either as an under-sown relay crop (to establish a winter cover crop or a forage crop) or as a service crop in a wheat-based rotation.

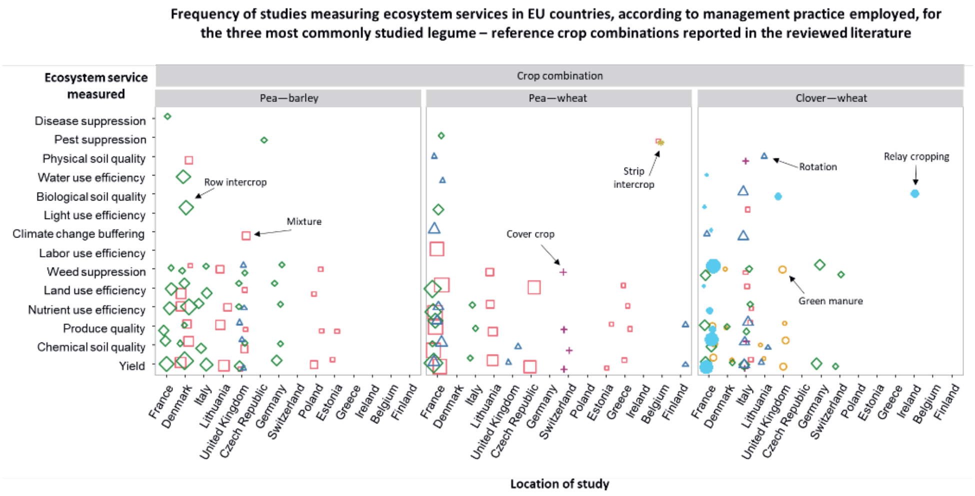
Frequency of studies measuring ecosystem services in EU countries, according to management practice employed, for the three most commonly studied legume – reference crop combinations reported in the reviewed literature

Figure 3.5. Frequency of studies measuring ecosystem services in the three most commonly researched legume–non-legume reference crop combinations (pea–barley, pea–wheat, and clover–wheat) in different locations in the EU, as reported in the reviewed literature. Symbols and colors correspond to the legume inclusion method employed in the study. The larger the symbol, the more studies on that combination; the largest symbol in the plot (Crop combination = Pea–wheat, x = France, y = Yield, inclusion method = Mixture) denotes 12 studies, and the smallest symbol (Crop combination = Pea–wheat, x = Belgium, y = Pest suppression, inclusion method = Strip intercrop) denotes one study. Location of study and ecosystem services are ordered according to the frequency with which they appear in the literature review database.

The concentration of research around production-related services in wheat- and pea-based cropping systems signals not only a well-known agronomic synergy (Jensen et al. 2020), but is also likely reflective of a long history of co-evolution towards specialization at all levels of the agri-food chain. Magrini et al. (2016) presented a comprehensive analysis of how this co-evolution occurred and led to what they call the "marginalization" of legume crops in France specifically and in the EU more generally. They described how current economic structures, built upon choices made decades prior, re-enforce lock-ins by rewarding the adoption of major crops (in Europe, cereals), rather than minor crops (like legumes). In their analysis of grain legumes in France, Magrini et al. (2016) found these initial choices to be rooted in historical European-wide preferences for fertilized cereals and imported soybean, which led to increasing returns to adoption of these practices, reinforcing the initial choices and hammering in the socio-technical lock-in. Examples from outside Europe may provide useful insights into how historical trends can alternatively be redirected towards including legume crops, e.g. through breeding, state policy, and farmers' networks, as in Brazil (de Sowa and Busch 1998; Cattelan and Amélio 2018).

Currently, the drive to produce wheat in Europe is powered largely by dietary preferences and industrialized processing, which demand highly standardized bread-quality grains that depend on heavy N fertilization. Meanwhile, the economic competitiveness of soybean meal, coming into Europe through international trade as the dominant source of protein-rich animal feed supporting the demand for meat (Kezeya Sepngang et al. 2020), stimulates research institutes to focus on locally-adapted and cost-effective feed-protein replacements, of which grain pea is one. Societal demand in the EU further fuels the desire to find local and non-genetically modified alternatives to internationally produced soybean, with grain pea again appearing as a viable alternative (faba bean is gaining some attention in this regard as well (cf. Jensen et al. 2010)). Our review results suggest that together, these drivers make plausible a heavy focus on wheat (and in colder climates, barley) and pea intercropping systems where the value of the legume is in its dual ability to reduce the need for artificial N fertilizer supplied to the cereal and to provide a high quality and locally produced animal feed source. This kind of positive mutual reinforcement between market demand and research demand further reinforces a production, research, and market climate that is unaccommodating to novel, less productive, and diversified crops (Meynard et al. 2018).

3.4. Under-studied services: does research targeting address farmers' interests?

The large gaps in the legume–ES matrix (top right area of Fig. 3.3) highlight the services that have so far been infrequently studied in cropping systems with legumes compared to systems without. For ES with less direct relevance to marketability and profit (e.g. climate change buffering, water use efficiency) there are fewer studies in the database (45 and 13 studies, or 9.6% and 2.8% of the total, respectively), and those present are focused primarily on legumes included in cereal-based systems. We found only four studies which directly measured associated biodiversity as an effect of legume presence, representing less than 1% of total database entries. Very few studies addressed pest and disease suppression (11 and 6 studies, or 2.4% and 1.2% of the total, respectively), and among these we found contrasting reports, with both positive and negative effects of legumes on ES delivery described. In such cases, it might be that there are strong drivers of variability, for instance seeding ratios (e.g. Schoeny et al. 2010), intercropping methods (e.g. Lopes et al. 2015), or residue management techniques (e.g. Abou Chehade et al. 2019), which affect the service delivery for better or worse. The scarcity of published research exploring these interactions suggests that research has not sufficiently addressed ES with high potential for variability in delivery by legumes, and that further research is needed that connects variability in ES delivery to environment- and management-related variables (Stagnari et al. 2017). It may also be that studies on some topics, for example disease, are designed to make comparisons between legume species or cultivars rather than between systems with legumes and those without. In these cases, the structure of our review may not have allowed capturing the full range of current scientific knowledge.

Drawing on previous studies, there is evidence that farmers seeking support for the adoption of new methods may have interests that are not well reflected by the research foci dominant at institutional levels. In the LegValue project, one of those in the Horizon 2020 crop diversification cluster, a survey exploring legume adoption among European farmers (Pelzer et al. 2019) showed that in addition to the more widely assumed need for support in the development of market and value chains, the ES on which farmers indicated they needed more information in order to more successfully incorporate legumes into their cropping systems were closely aligned with the apparent knowledge gaps we found in the literature. Pelzer et al. (2019) found that among farmers' top interests was to have better support on crop management topics; in particular farmers wanted information on pest, disease, and weed control in legume-inclusive systems. These findings reflect those of Mawois et al. (2019) who did a similar study in France and showed that this kind of crop management knowledge was pivotal in the success of farmers who had made a stable transition towards legume-inclusive systems. In their broader study on crop diversification, Morel et al. (2020) also found that evidence of farm-level sustainability benefits was a key factor in whether or not conventional farmers would try adding new crops to their rotations.

Despite farmers' apparent interests, our review suggests that institutional research specialization remains closely linked to production specialization and market demand. Historical cropping specialization away from legumes, as discussed in the previous section, appears to have led to a concurrent knowledge drain away from legume crops, translating into learning that enables higher yields of major crops (mostly cereals) rather than learning that facilitates the adoption of new crops previously considered as minor and of low interest for economic actors and scientists. A clear example exists in France, where funding for research and development of major crops comes in part from a tax paid on the sale of these same crops, whereas lesser-grown but potentially interesting crops do not receive such funds (Magrini et al. 2016). Such a feedback mechanism leads to a reinforcement of selective knowledge development through so-called "learning economies" (Callon and Bowker 1994) where rewards for scientific knowledge development are greater in domains populated by many scientists who can understand, refer to, and disseminate the new knowledge contributed (Pimbert 2018). In other words, specialization on the farm and in the market stimulates knowledge specialization among researchers (and vice versa), widening the learning differential between the already-dominant knowledge arenas and potential alternative practices (Vanloqueren and Baret 2009), in spite of farmers' expressed interests.

3.5. Small-scale and short-term: evidence of resource constraints?

Farmers in the LegValue survey also cited economic and cultural ES in their expectations of what legumes could provide (Pelzer et al. 2019), few of which are documented in this literature review. Services for which the benefit may be delayed (e.g. economic benefit of residual N provision to post-legume crops beyond a single season (Pelzer et al. 2012)), and for which the underlying processes operate at the farm or landscape scale (e.g. supporting beneficial insect populations with large ranges of movement (Schellhorn et al. 2014)), are generally not well represented in the literature returned by our search. Of the studies we entered in the database, 92% focused on measurements taken and analyzed at the plot level, and 75% measured the legume effect within the same season. Half of these also measured effects in the immediately following season, but it was not well indicated whether measurements were continued beyond the first season after legume inclusion.

The focus we saw on short-term plot-level experiments could be because studying processes that operate at wider spatial and temporal scales does not fit current research organization and resourcing. It may also be that these topics are studied in experimental designs that do not fit within the scope of our review. For example, Rundlöf et al. (2014) provide a valuable analysis of the role of late-flowering clover fields in habitat and resource provisioning for bumble bees which shows the importance of legumes for supporting pollinators at the landscape scale. The design of their study, however, did not meet our inclusion criteria so it was not considered in our analysis. Another consequence of the focus of our review on empirical field trials at cropping system level was the exclusion of the wide body of literature utilizing models. Models are often used to address questions of scale (especially temporal). However, Costa et al. (2020) also observed a focus on shorter-term effects in their review of life cycle assessments of legume-inclusive cropping systems, in line with our results for field trials.

In a field trial setting, large areas are needed for unravelling spatially explicit processes, and long-term studies are needed for examining temporally influenced (e.g. N-fixation, phosphorus mobilization, or weed, pest, and disease control) or building (e.g. soil organic matter increase or decrease, soil microbial and macro-fauna diversity, weed diversity, physical soil quality) services. Such spatial and temporal requirements go beyond current conventions on what constitutes an agronomic field trial as supported by short-duration research funding schemes, reinforcing gaps in this knowledge. Furthermore, research that takes multiple years to conduct has a lower turnover rate from inception to publication (Vanloqueren and Baret 2009). While these constraints are understandable, the strength of farmers' interests, as illustrated by both Mawois et al. (2019) and Pelzer et al. (2019), should provide motivation to overcome these challenges and direct new research toward understanding the effects of legume-inclusive cropping systems on ES provision at longer temporal and broader spatial scales. Morel et al. (2020) specifically call out a need for farm-level research on longer rotations and systemic long-term assessment of crop diversification benefits, while Voisin et al. (2014) argue for an even wider approach that includes processing and consumption. Recent studies which take a systems-level co-design approach to innovation in legume-inclusive systems (such as Reckling et al. 2020) provide good examples for how to do this and can complement reports looking at production and consumption dynamics (e.g. Kezeya Sepngang et al. 2020).

3.6. Ways forward for ecosystem service research in legume-inclusive systems

In agricultural research systems, multiple determinants can be identified which together shape and direct the technological regime, dictating the choice of which technologies are studied and developed, thus structuring the development of technological (and knowledge production) trajectories (Vanloqueren and Baret 2009). From the signals highlighted in this review (e.g. an abundance of research on production-related ES in pea–cereal systems), we infer that the narrow focus of legume research on particular ES in the EU is likely the result of multiple factors acting together at all levels of the science and technology landscape. A key factor may be the market-driven dominance of few legume species and management systems, which directs researchers to narrow in on production-related ES of particularly these species; investigating this possible causal relation would enhance existing insights on barriers to legume adoption in Europe. The area of land devoted to legume production in the EU overall is already small, and within this area a relatively large portion is dedicated to the few crops we identified as being most studied (Kezeya Sepngang et al. 2020). These are also the legumes with the greatest market demands (with the exception of soybean, which is growing in area and market demand but for which there was less ES research (Kezeya Sepngang et al. 2020)), with pockets of variation in regional specialization that likely correspond with local market opportunities.

Knowledge on ES delivery is one piece of the larger puzzle of how to break down barriers to legume adoption and crop diversification in general in the EU. Our discussion here has shown the importance of reflecting on the role research on ES plays within that puzzle, particularly in regard to supporting farmers' knowledge needs. Beyond the farm level, it appears that the limited and productivist-oriented research that historically predominates the literature does not fully support the sustainability directions aspired to by the European Commission. Low-input, diversified, and biodiversity-based initiatives such as those included in the EU Green Deal could be better underpinned by agroecological systems research that examines a wider spectrum of ES delivery mechanisms, contexts, and systems, within a framework that incorporates other social and market concerns. This review reveals a need for projects that will follow the Horizon 2020 crop diversification cluster to take stock of current research and critically reflect on the potential lock-ins and their causes that may be influencing research agendas. It may be that reformulating research priorities is necessary in order to fill the most consequential knowledge gaps.

This study does not account for the likelihood of publication biases, nor does it quantify the effect of incorporating legumes on the delivery of the studied ES. Instead, the usefulness of this study lies in its potential to catalyze critical reflection, and to lead to general recommendations for how to add breadth to current and future research portfolios. Added breadth could be achieved by putting emphasis on minor and underutilized legume species for human consumption (e.g. chickpea, lentil) which may soon see a rise in consumer demand (Vasconcelos et al. 2020), and by exploring ES delivery in more diverse spatial and temporal arrangements that stimulate agro-biodiversity at both fine and course resolutions. Increasing the breadth of current agroecological research targets would add value to other efforts contributing to breaking down adoption barriers. To that end, a recommended next step would be to quantitatively review the ES effects of introducing legumes to current cropping systems, particularly for those ES with direct agroecological interest to farmers, although this may be challenging given the lack of research on certain ES. Further, it would be useful to simultaneously examine the sources of variability in the delivery of those ES, so that cropping systems can be adapted to local preferences, practices, climates, and soils. Together, this information would support farmers in fitting legumes into existing systems, allowing legume inclusion to act as the stepping stone towards greater European crop diversification that proponents expect it to be.

3.7. Conclusions

With this review we sought to systematically inventory the published research on ES delivery from legumes when introduced in current European cropping systems, and to subsequently identify areas of knowledge abundance and scarcity with potential relevance for un-locking barriers to legume adoption. Our findings suggest a need to extend and diversify research on ES from legumes to include multi-criteria and multi-scale approaches to ES not yet well explored, rather than reinforcing knowledge on known ES, crop combinations, and management systems which reflect a narrow market-driven paradigm. It is important to be critically reflective of the status quo of research trajectories, not only in Europe but also globally, because they can act as a selection device limiting future science and technology development. When it comes to socio-technical lock-ins in agriculture, such as the narrow focus we observed on few studied legume species, market uses, and ES delivered, choices made decades ago apparently still have effects that are self-reinforcing, leading to the co-evolution of specialized farms, narrowly focused research and knowledge-support agendas, and few dominant industry and market chains. The apparent misalignment between what farmers want to know and what is present in the peer-reviewed literature provides compelling stimulus to redirect research agendas and foster multi-actor engagement towards work that directly supports farmers in developing diverse, productive, and sustainable legume-inclusive cropping systems, particularly in countries currently underutilizing legumes. As long as research remains narrowly targeted, farmers and advisors will remain under supported in efforts to fully exploit the potential benefits of crop diversity. Connecting research needs with the topics farmers are interested in, and using this information to direct research agendas, is imperative for keeping research timely and relevant, and for supporting the sustainability ambitions of the European Commission.

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Appendix 3

A3.1. Literature search terms

Search terms and Boolean operators used in the Scopus search:

TITLE-ABS-KEY((agricult* OR agronom* OR farm*) AND (agrobiodivers* OR polyculture OR “diversi* farm” OR "crop* diversi*" OR “multiple crop*” OR "mixed crop*" OR "variet* mix*" OR intercrop* OR "strip crop*" OR "row crop*" OR "relay crop*" OR "crop* rotation*" OR "green manur*" OR "cover crop*" OR "under sow*" OR agroforest* OR forage OR legum*) AND (“ecosystem service*" OR sustainab* OR "soil structure" OR "soil organic matter" OR "soil quality" OR "soil carbon" OR "carbon sequestration" OR "soil erosion" OR "soil biological diversity" OR "soil biological activity" OR "biogeochemical cycling" OR run-off OR "surface soil moisture" OR "water holding capacity" OR "water infiltration" OR porosity OR permeability OR percolation OR "water use efficiency" OR "aggregate formation" OR "aggregate stability" OR "soil aggregat*" OR "cation exchange capacity" OR "microorganism abundance" OR mycorrhiza* OR "*nutrient* management" OR "nutrient retention" OR "nutrient cycling" OR micronutrient* OR macronutrient* OR "nutrient* uptake" OR (“nitrogen W/2 leaching”) OR (“nitrate W/2 leaching”) OR (“phosph* W/2 runoff”) OR (“phosph* W/2 solubilisation”) OR ("weed W/4 control") OR "weed density" OR ("weed W/4 suppression") OR ("weed W/4 management") OR "weed pressure" OR ("weed W/4 abundance") OR "weed seed density" OR "weed biomass" OR allelopath* OR ("disease W/4 management") OR ("disease W/4 control") OR ("disease W/4 suppression") OR ("disease W/4 incidence") OR ("disease W/4 resistance") OR ("disease W/4 prevention") OR ("pest W/4 suppression") OR ("pest W/4 management") OR ("pest W/4 control") OR ("pest W/4 regulation") OR ("pest W/4 abundance") OR ("pest W/4 incidence") OR biocontrol OR "biological control" OR predation OR natural enem* OR herbivor* OR ("pest W/4 damage") OR "crop loss" OR "beneficial insect*" OR "beneficial arthropod*" OR pollinat* OR biodiversity OR “break crop” OR "greenhouse gas*" OR "energy use" OR "energy consumption" OR "energy use efficiency" OR emission OR adapt* OR "carbon capture" OR “nitrous oxide” OR *yield* OR producti* OR "land equivalen* ratio" OR "produce quality" OR "grain protein content" OR "farm* income" OR "farm labor" OR "farm* revenue" OR ("cultivation W/4 cost") OR "farm profit*" OR “economic risk reduction” OR recover* OR resilien* OR stabil* OR resistance OR robust*) AND (legum* OR alfalfa OR lucerne OR chickpea* OR *clover* OR fava* OR faba* OR lentil* OR lupin* OR pea* OR soy* OR vetch* OR "medicago sativa" OR "cicer arientum" OR trifolium OR "vicia fava" OR "lens culinaris" OR "lupinus genus” OR "pisum sativum" OR "glycine max" OR "vicia sp."))

A3.2 Prisma diagram

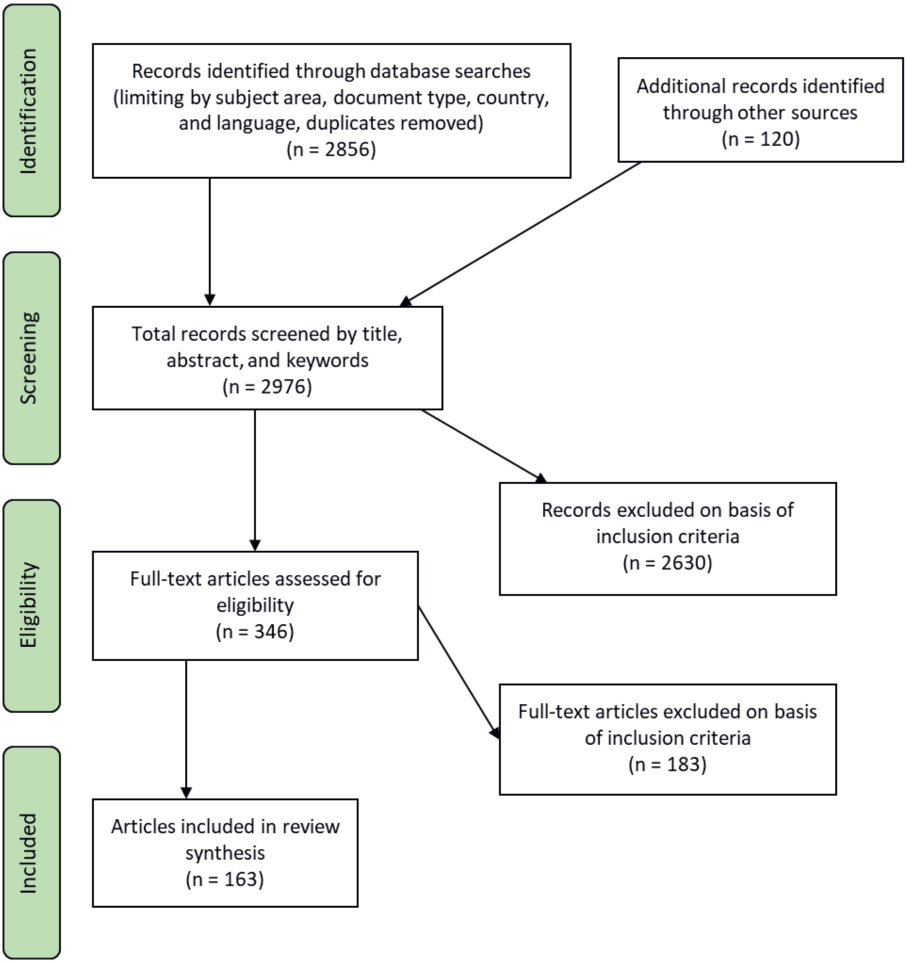

Figure A3.2.1. Prisma diagram (following Moher et al. (2009)) showing record of the systematic literature search. Eligibility was determined on the basis of four inclusion criteria: i) the research was conducted in the EU28, Norway, or Switzerland, ii) the research involved a field experiment (on-station or on-farm, no pot trials), iii) an ecosystem service other than or in addition to yield was measured, and iv) the research compared a cropping system with legumes included to a reference system without legumes. Modelling studies (including lifecycle assessments), reviews, and meta-analyses were excluded.

A3.3. Reviewed literature

A complete list of the literature reviewed in this chapter can be found in the supplementary material for the published version of this article, available open access at:
https://doi.org/10.1007/s13593-021-00678-z

Chapter 4

Redefining the field to mobilize three-dimensional diversity and ecosystem services on the arable farm

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Abstract

In this article we explore the concept and implications of three-dimensional (spatial, temporal, and genetic) in-field crop diversification to inform systems redesign towards ecological intensification. We first present a conceptual framework for classifying diversity in arable contexts. We then apply the framework to analyze two long-term systems experiments in The Netherlands where spatial and genetic diversity measures were implemented via strip, mixed, and intercropping with the aim to increase ecosystem service delivery: incidence and spreading rate of late blight (*Phytophthora infestans*) in potato (*Solanum tubersosum* L.), and biocontrol control potential in wheat (*Triticum aestivum* L.). In the case of late blight, potatoes planted in strips had significantly lower disease incidence than the monoculture reference across all years, and adding cultivar mixing within the strip was more powerful in mitigating late blight than spatial diversification alone. In the case of biocontrol in wheat, strips supported significantly larger (for all but one taxonomic group) and significantly more diverse epigeic natural enemy populations than the sole culture reference in all years. However, the addition of species mixing within strips did not further increase biocontrol indices compared to sole-wheat strips. These results imply that compromises between management complexity and ecosystem service enhancement are achievable through strip cropping, an operable practice with current machinery, and one that does not require a thorough reconfiguration of the production system. The three-dimensional diversity framework proved useful for unpacking experimental outcomes in terms of diversity-mediated mechanisms, however it requires further development before it can be used to facilitate multi-objective optimization.

Keywords: Strip cropping; intercropping; ecological intensification; disease mitigation; biological pest control

4.1. Introduction

In arable farming, the field is an important management unit which shapes how a farmer conceptualizes and executes cultivation activities. In Europe as in other parts of the world, the initiation of agricultural industrialization efforts post-WWII (in part supported by land re-allotment and consolidation policies) led to a change in the size, composition, and configuration of arable fields as farms adapted to accommodate larger farm machinery, a drive to specialize, and the demands of new economies of scale (Jepsen et al. 2015). Over the last several decades, these adaptations have led to a general shift towards larger arable fields, the domination of monocropping, and simplified agricultural landscapes (Eurostat 2018; van der Zanden et al. 2016; van Vliet et al. 2015).

In combination with how a farmer manages it, field size, composition, and configuration dictate what effect arable farming has on the delivery of various ecosystem (dis)services (Fahrig et al. 2015; Sirami et al. 2019). A monocultural approach to arable agriculture enables farmers to treat entire fields, no matter how big, as a single unit of management where cultivation tasks may be executed with efficiency by large-scale machinery. However, large extents of genetically uniform plants rarely occur in nature, and maintaining them in agriculture requires heavy reliance on external inputs and control-driven management. While heralded as technological breakthroughs that helped reduce hunger worldwide (i.e. the Green Revolution), it is now known that widespread applications of synthetic fertilizers and crop protection products, together with concurrent agricultural landscape simplification, have contributed to a cascade of failing ecosystem controls and the overstepping of multiple planetary boundaries (Campbell et al. 2017; Kinzig et al. 2006).

In low-diversity arable systems that rely heavily on external inputs, crop production capacities are exploited at the cost of ecological processes which support and regulate natural systems (Foley et al. 2005; Haddad et al. 2015; Patzek 2008; Tilman et al. 2011). A logical solution to restoring these processes would be to bring diversity back into the arable field, as lessons from ecology and agronomy show that diversification is a key ingredient in both productivity and the delivery of other ecosystem services in (agro)ecosystems (Barot et al. 2017; Beillouin et al. 2019; Kremen and Miles 2012; Tilman et al. 2001). In agriculture, crop diversification has been promoted as a way to increase resource use efficiency, improve soils, and mitigate the spread of pests and diseases (Malézieux 2012; Duru et al. 2015b), and has been found to stabilize food production over time (Renard and Tilman 2019). Implementing diversification measures, however, requires a different approach to field-level crop management than the typical monocultural system, and therefore requires a rethinking of how the notion of a ‘field’ is defined. Additionally, fitting diversified production systems within current industrial agricultural paradigms presents many challenges and uncertainties.

Conceptually, definitions of ‘diversity’ differ between farming and research contexts, and a unified understanding of the concept is lacking (Hufnagel et al. 2020). How to both qualify and quantify diversity at field and farm levels are open questions. Synthesizing actionable knowledge from research on the relationships between crop diversity and ecosystem service delivery, production, and management practices would greatly benefit from the structure of a common framework (Geertsema et al. 2016). For farmers, such a framework could also be useful for guiding the choice and implementation of management practices based on desired ecosystem services. The first objective of this paper is therefore to explore how farming practices mobilize diversity and to integrate these concepts into a common framework.

Practically, farmers encounter socio-technical lock-ins at all levels of production, from field to market, which inhibit and dissuade them from diversifying (Magrini et al. 2016; Meynard et al. 2018; Roesch-McNally et al. 2018). In addition to technological and marketing support, knowledge on the ecosystem service benefits of crop diversification has been identified as a key lever for helping European farmers overcome these lock-ins (Mawois et al. 2019; Morel et al. 2020; Pelzer et al. 2019). In particular, conventional and specialized farmers have identified that they need this knowledge before they will consider adopting new crops (Morel et al. 2020). Clear evidence of the benefits of combining diversification measures is therefore needed if farmers are expected to move away from large-scale monoculture systems towards more diversified arable fields with more complex management demands (Duru et al. 2015a). Farmers, however, are not the only food system actors facing lock-ins: research agendas are also limited by the influence of specialization in field and market domains (Magrini et al. 2016; Vanloqueren and Baret 2009). While it is known, generally, that increasing the resolution of diversity within the arable field affects ecological processes in different ways and at different scales (Duru et al. 2015b), how different diversification measures interact to deliver multiplied, cascading, or diminished benefits is less known (Bommarco et al. 2013; Caron et al. 2014; Losey and Vaughan 2006). The second objective of this paper, therefore, is to examine examples of multi-dimensional diversification in practice, and to analyze the effects of these practices on the delivery of ecosystem services relevant to European farmers.

In Section 4.2 we present a conceptual framework for classifying what we call the *three dimensions of diversity* that can be leveraged within the arable farm field; these are *time*, *space*, and *genes*. We begin by briefly reviewing current knowledge on the effects of temporal, spatial, and genetic diversity on ecosystem service delivery in arable cropping systems. We then present a heuristic visualization which combines the dimensions into a three-dimensional space, and position field-level management practices within that space. Synthesizing knowledge of the mechanisms behind the effects of each diversity dimension with an understanding of how the dimensions can be mobilized through practical field management provides a necessary framework for understanding how the unit of management—and thereby the fundamental notion of the arable field—can be redefined to promote diversity.

In Section 4.3 we introduce the empirical cases, two long-term strip cropping experiments conducted in The Netherlands, and explain our data collection and analysis methods. These experiments tested the effects of two-dimensional (genetic and spatial) diversification on the delivery of two ecosystem services relevant to Dutch farmers: biocontrol potential in wheat (*Triticum aestivum* L.) and late blight mitigation in potato (*Solanum tuberosum* L.). *Phytophthora infestans* (Mont.) de Bary (here forward referred to as *PI*), is an oomycete and the cause of potato late blight, a pernicious disease that infects potato leaves and stems, causing above-ground biomass to die off and tubers to rot. Late blight is of major concern in the Netherlands where conducive conditions are prevalent during the growing season and potatoes are a tremendously important economic industry, and an integrated approach to control is needed (Haverkort et al. 2008; Lammerts van Bueren et al. 2008; Pacilly et al. 2018; Pacilly et al. 2019). Cereals are also an important crop in the Netherlands, and in cereals aphids are an abundant pest that can cause substantial yield losses—losses that are projected to increase concurrently with climate change (Dedryver et al. 2010; Deutsch et al. 2018; Tatchell 1989). Like other insect pests, control of aphids is enhanced by the biocontrol provided by natural enemies present in the agroecosystem (Hatt et al. 2017). In both experiment cases, we hypothesized that mobilizing multiple dimensions of diversity simultaneously, i.e. 'stacking' diversity measures in the arable field, would result in increasing returns in the form of enhanced ecosystem service delivery (disease mitigation and biocontrol potential) compared to a monoculture.

In Section 4.4 we present the results of the two empirical cases, and in Section 4.5 we unpack the results within the frame of the three-dimensional diversity concept, reflecting on the stacking diversity—ecosystem service hypothesis in light of the two-dimensional diversity examples. We conclude the discussion with a theoretical examination of the implications and prospects of mobilizing all three diversity dimensions in concert —i.e. redefining the composition, configuration, and management of the arable field.

4.2. Conceptualizing three-dimensional diversity

4.2.1. Temporal, spatial, and genetic diversity

Taking a 'true monoculture' (the same crop cultivar planted in the same field every year) as an illustrative baseline, diversity can be introduced to the arable field in numerous ways, all of which can be categorized in terms of *temporal*, *spatial*, or *genetic* diversification. Following Kremen and Miles (2012) and Wezel et al. (2014), we refer to these categories as the *three dimensions* of diversification in agroecosystems. Increasing diversity in each dimension involves practices that increase the number of crop cultivars, species, or farm components (e.g. trees, livestock) in a field within a given unit of time (i.e. a field—time unit), and implies an increase in the resolution at which those practices are implemented (Fig. 4.1). Higher resolution is here equated with greater heterogeneity within the field—time unit, qualified by a reduction in the size of the smallest homogenous unit within that field. Homogenous units within the field (areas planted with a single crop species and cultivar) could range in size and shape from several hectares, to strips of several crop rows, or to small 'pixels' containing an individual plant or a cluster of plants. Increasing the resolution of diversity in each dimension is known to have different effects on ecosystem service delivery in agricultural contexts, which can be explained by differences (and sometimes overlaps) in the fundamental ecological mechanisms relevant to and activated at temporal, spatial, and genetic scales.

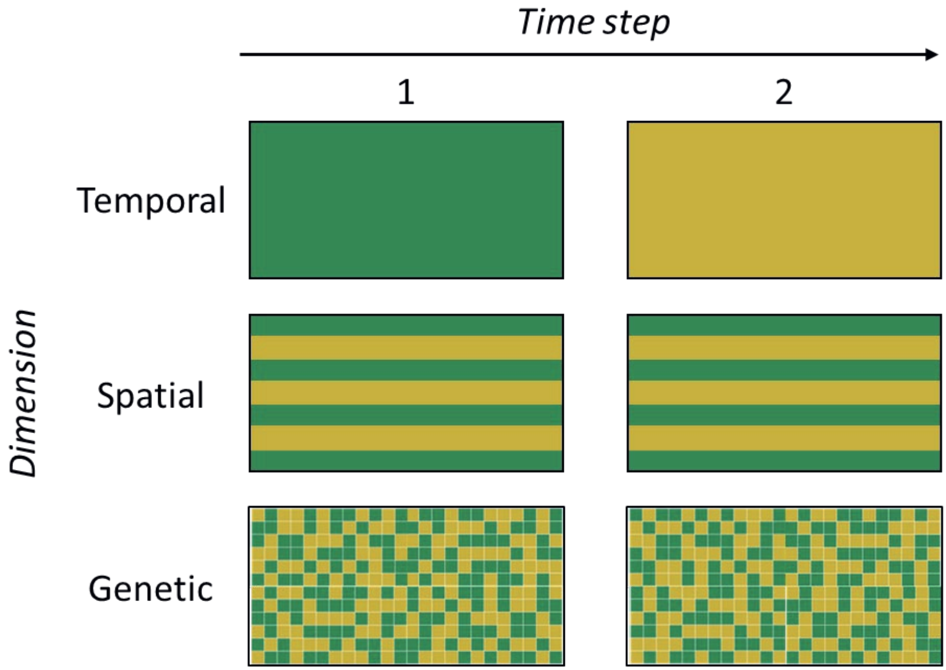

Figure 4.1. The three dimensions of diversity that can be mobilized through field management practices, visualized as a field—time unit over two time steps. Each color represents a different crop or cultivar.

Crop rotation—sowing fields with a different crop each year in a pre-determined sequence of two or more years—is a commonly employed method of diversification. The resulting *temporal* diversity is known to benefit agroecosystems by breaking transmission cycles of soil- and residue-borne pathogens, and overwintering pests; this is paramount to the underlying rationale for using rotations (Leoni et al. 2015). Additionally, crops access, exploit, and influence soil resources differently. By rotating crops with differing nutrient demands, rooting behaviors, residue legacies, and mechanical cultivation needs, soil damage can be mitigated and soil resources maintained (Dogliotti et al. 2003; Venter et al. 2016), and weed suppression improved (Weisberger et al. 2019).

Genetic diversity is commonly studied and implemented in agricultural settings as cultivar or species mixtures (e.g. cereal—legume) uniformly sown and managed like a sole crop. Resource capture and use efficiencies are regularly found to be higher in mixtures than in sole crops, due to niche complementarity and facilitation (Hauggaard-Nielsen et al. 2008; Pelzer et al. 2012). Mixtures of species and cultivars are also known to have lower pest and disease infestations relative to monocultures, in part because mixing host and non-host species or cultivars dilutes the concentration of resources and disrupts the movement of pests and diseases through a crop stand (Lopes et al. 2015; Skelsey et al. 2005; Zhu et al. 2000). The diversity of habitats and resources provided by species mixtures may also support a greater abundance and diversity of natural enemies which contribute to the biocontrol of pests (Isbell et al. 2017; Poveda et al. 2008).

Although less well studied and less commonly applied in industrial arable fields, *spatial* diversification measures are known to provide similar ecosystem services as genetic measures within agroecosystems. Recent meta-analyses show that row and strip intercropping can substantially increase crop yields through niche differentiation (van Oort et al. 2020; Yu et al. 2015), as well as reduce disease incidence (Zhang et al. 2019) and pest infestation (Tajmiri et al. 2017). Similar to the mechanisms at work in genetic mixtures, spatial heterogeneity works to regulate pest and disease spread by mobilizing barrier effects which disrupt movement and dilute resources, as well as by creating micro climate effects (Hatt et al. 2018).

4.2.2. Visualizing a three-dimensional diversification space

Visualizing the diversification space helps to disentangle the dimensions of diversity at play in arable systems as they are activated through the implementation of farming practices, and several authors have offered useful approaches for doing this (e.g. Brooker et al. 2015; Duru et al. 2015b; Kremen et al. 2012; Wezel et al. 2014). Drawing on these examples, we propose a new heuristic visualization which illustrates the way field-level practices mobilize the three diversity dimensions. We visualize diversification as a three-dimensional space, and position farming practices within it (Fig. 4.2). Here we consider 'true monoculture' (the same crop planted in the same field every year) as an illustrative baseline, positioned at the spatial (x), temporal (y), genetic (z) point [1, 1, 1]. Moving up the axis of each dimension implies increasing field-level heterogeneity through practices that increase the resolution of diversification; the farther from the baseline of the figure, the more diverse the field—time unit and the higher the resolution of diversification. The total diversity of each practice has here been calculated simply as the sum of the three axis values to give a compound diversity score. Scores on all axes should be considered qualitative and relative.

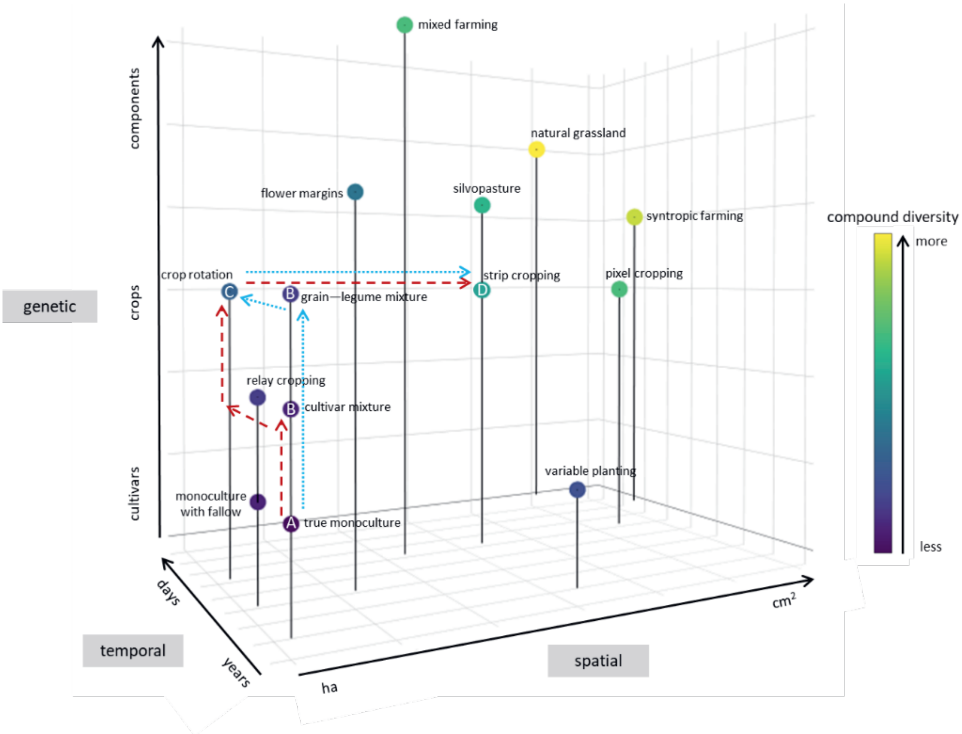

Figure 4.2. Heuristic visualization for understanding how field-level farm management practices mobilize the three dimensions of diversity. Diversification measures are positioned within a three-dimensional space where each axis moves from lower to higher heterogeneity (i.e. increasing resolution); scales are qualitative and relative. Starting with a ‘true monoculture’ as an illustrative baseline, the red dashed arrow (potato example) and blue dotted arrow (wheat example) show possible pathways through which a cropping system could be diversified in three dimensions, arriving at the management practice (strip cropping) examined in this paper. Color scale shows relative compound diversity scores, calculated as the sum of the x, y, and z values for each point.

In Fig. 4.2 we have traced two pathways illustrative of management practices which might be chosen by a farmer seeking to diversify arable fields, and which are later discussed in the empirical cases. In the example outlined by the red dashed arrow (Fig. 4.2, points A—D), we start with a hypothetical (albeit unrealistic) scenario in which the true monoculture (Fig. 4.2, point A) represents a field where a single cultivar of potato is grown season after season, year after year. Diversification can occur in three ways. First, introducing an additional cultivar, species, or component to the field enables a farmer to increase genetic diversity. In the hypothetical continuous potato system, adding the second potato cultivar and sowing as a homogenous mixture results in a move up the genetic axis while maintaining the baseline position on the spatial and temporal axes (Fig. 4.2, red dashed arrow to point B).

Next, the baseline can be extended on the temporal axis by introducing a fallow, new species, or additional components over time. The addition of a fallow in the all-potato rotation would move the point up only on the temporal axis. By introducing a crop rotation of two or more crop species rotated sequentially over cropping seasons or years, the point moves up both the temporal and genetic axes (Fig. 4.2, red arrows to point C).

Finally, to diversify the system spatially, a farmer can introduce methods that increase the resolution at which multiple crop cultivars, species, or farm components are physically arranged within the field at a given point in time. In the potato example, point C can be moved up the spatial axis by implementing a practice that delineates spatially explicit multi-crop arrangements within the field (Fig. 4.2, red arrow to point D). Here the illustrative practice is strip cropping, in which it is assumed that crops are grown in multi-row strips in an alternating pattern of at least two crops.

We posit that visualizing the diversification space can help to disentangle how field-level practices function to deliver agroecosystem services: by recognizing which dimension(s) of diversity are activated when a farming practice is implemented, results may be analyzed and understood through the lens of the mechanisms active in each dimension. We propose that this heuristic, together with knowledge of the mechanisms behind the ecosystem service delivery outcomes of each diversification dimension, be used to unpack experimental results and to position such results within the conceptual premise of redefining the arable field. We will demonstrate how this may be done with empirical examples in Sections 4.4 and 4.5.

4.3. Empirical cases: materials and methods

To test the stacking diversity hypothesis and illustrate an application of the conceptual framework presented in Section 4.2, we analyzed the effects of multi-dimensional crop diversification on two ecosystem service indicators in arable cropping systems using multi-year data (2010-2017) from two long-term organic systems experiments in the Netherlands. The two empirical cases analyzed are illustrated in Fig. 4.2 as the red dashed arrow (potato case) and the blue dotted arrow (wheat case). In both cases, two dimensions of diversity were mobilized through the management practices of strip cropping (spatial diversity) and crop mixtures (genetic diversity). Both systems experiments followed diverse crop rotations, however we do not examine the temporal dimension in this analysis.

4.3.1. Experiment sites

The experiments were located at two Wageningen University & Research experimental stations: the Field Lab for Agroecology and Technology in Lelystad (52°32’30”N, 5°34’20”E) and the Droevendaal Experimental Farm in Wageningen (51°59'30"N, 5°39'50"E). Both experiments were managed according to Dutch organic standards and regulations (Skal 2020). For both potato and wheat, three experimental treatments were tested: 1) large-scale sole-cropped reference fields (REF), 2) sole-crop, single cultivar strips (STRIP), and 3) mixed-species or mixed-cultivar strips (STRIP_MIX). For potato, the STRIP treatment was planted with the non-

PI resistant cultivar Agria, and mixed strips consisted of a cultivar mixture which included one non-*PI* resistant cultivar (Agria) and two *PI*-semi-resistant cultivars (Carolus and Alouette). For wheat, mixed strips were sown as a polyculture composed of a cross-composite population of spring wheat and faba bean (*Vicia faba* L.). In Lelystad, only REF and STRIP potato treatments were present, and in Wageningen all three treatments were tested in both potato and wheat. In 2017 in Wageningen, the additional experimental factor of strip width was introduced in the potato plots, and two strip widths were tested (3 m and 6 m) in comparison to the large-scale reference. Basic experimental details and environmental characteristics at each study site, including mean yields obtained per treatment, are outlined in Table 4.1. Maps of the experimental layouts are provided in Appendix A4.1.

4.3.2. Data collection

PI infestation in potato

Over the multiple years of the experiments, different scoring methods, all using visual observation, were employed to assess *PI* infection: leaf area affected (%), plants affected (%), severity (%), and infected leaflets per m^2 (for explanations of these metrics, see: EPPO 2008; Madden et al. 2007). Within years, the same scoring method was used in both the strips and the REF. Only plants of the non-*PI* resistant cultivar were scored for disease infection. At Wageningen in 2017, the same plants observed in the first round were then revisited at each subsequent round until the plot was terminated. Following Dutch regulations for the management of *PI* (De Minister van Landbouw 2017), plants were terminated when plot-level infection severity reached 20 infected leaflets per m^2. The methods used and number of *PI* observations made each year and at each experimental location are outlined in Table 4.2.

Table 4.1. Site characteristics and experiment details, including mean yields per treatment each year, at the two experiment sites (the Field Lab for Agroecology and Technology in Lelystad and Droevendaal Experimental Farm in Wageningen, both in the Netherlands), 2010-2017.

Site characteristics		Lelystad (2010-2016)	Wageningen (2015-2017)
	Soil texture	Light clay / sandy clay loam	Loamy sand
	OM content (%)	4.29	3
	Annual temp in °C (average during study timespan)	10	11
	Annual rainfall in mm (average during study timespan)	846	973
	Crop rotation	potato, grass—clover, cabbage, spring wheat, carrot, faba bean—spring wheat mixture	potato, grass—clover, grass—clover, winter oil seed rape, winter triticale, spring wheat
	Strip dimensions (length x width)	80-125m x 3.15m	240m x 3m
	Reference field dimensions	2-3 ha	0.5-3 ha
	Tillage practice	Non-inversion	Minimal tillage

Crop Yields		potato yield (t ha^{-1})		wheat yield (t ha^{-1})
		Lelystad 2010-2016	Wageningen 2017	Wageningen 2015-2017
	Large-scale reference	29.09 †	37.14	2-3 *
	STRIP_3m	30.39	41.23	2.68
	STRIP_MIX_3m	32.72	47.65	1.71
	STRIP_6m	NA	37.41	NA
	STRIP_MIX_6m	NA	43.55	NA

* Reference plot yields were not measured, farmer estimated 2-3 t^{ha-1} average

† Reference yields only recorded in 2014 and 2016

Table 4.2. Infection scoring method (unit of measurement) and number of late blight (*P. infestans*) observations made in potato crops at the Lelystad and Wageningen field experiments in the Netherlands, 2010-2017.

Year	Infection unit measured	Number of experiment blocks	Number of observation rounds	Plants inspected first round[*]	Support (total plant inspections)
Lelystad					
2010	leaf area affected (%)	1	1	30	180
2011	leaf area affected (%)	3	1	25	450
2012	leaf area affected (%)	2	2	35	1015
2013	plants affected (%)	2	6[†]	100	700
2014	severity (%)	2	3	35	5180
2015	severity (%)	2	3	35	2240
2016	severity (%)	2	6[‡]	35	2730
Wageningen					
2017	infected leaflets per m^2	3	12	360	3084

[*] Total number of plants inspected per round decreased throughout the season as plots were terminated, having reached the regulatory threshold for late blight infection. As long as all plots were not yet terminated, the same number of plants was inspected in subsequent rounds as in the first round.

[†] During the first five observation rounds, no *PI* infections were encountered

[‡] REF field was terminated after first assessment

Epigeic natural enemies of aphids in wheat

As an indicator of biocontrol potential for aphids in wheat, we assessed the prevalence and diversity of their epigeic natural enemies (NE). NE were captured and identified at the Wageningen experiment across three growing seasons (2015-2017) in the two strip treatments (STRIP and STRIP_MIX), and in the REF, using pitfall trapping. Pitfall traps were constructed using a transparent plastic cup (8.5 cm diameter) placed in the soil so that the rim of the cup was level with the soil surface. Cups were filled with approximately 100 ml of water mixed with one drop of neutral soap, covered with a plastic roof (12.5 cm diameter) positioned 2 cm above the soil surface, and left in the field for 2-5 days, depending on the weather conditions (at cooler temperatures, traps were left out longer) (Fig. 4.3). In the strip-cropped treatments, one pitfall trap was placed in each experimental plot (*n* = 6 per treatment). In the large-scale monoculture field, pitfalls were placed within a strata 34 m from the field edge (the center of the field), with six replicates in 2015 and 2016 and four replicates in 2017.

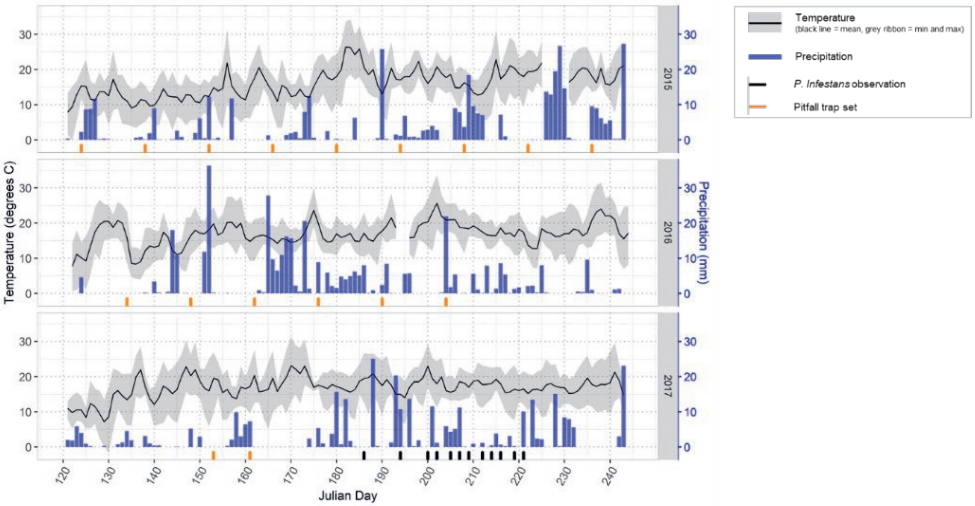

Figure 4.3. Weather at the Wageningen site during experiment observations, 2015-2017. Orange ticks on the x axes mark pitfall trapping dates, black ticks mark PI observation dates. Black line shows mean temperature (degrees Celsius), grey ribbons span daily minimum and maximum temperatures (degrees Celsius), and blue bars are the sum daily precipitation (mm). Data obtained from the Royal Netherlands Meteorological Institute (KNMI) and the weather station De Veenkampen operated by Wageningen University.

Arthropods captured in the pitfall traps were preserved in 70% ethanol and identified in the laboratory. Only known predators to aphids (following Schmidt et al. 2003) were identified and counted. These were: adult and larval ladybeetles (*Coccinellidae*), hoverfly larvae (*Syrphidae*), adult and larval lacewings (*Chrysopidae*), parasitoid wasps (*Hymenoptera*), spiders (*Araneae*), harvestmen (*Opiliones*), adult and larval carabids (*Carabidae*), and adult and larval rove beetles (*Staphylinidae*). Parasitoid wasps, spiders, and harvestmen were identified to the level of Order; ladybeetles, hoverflies, lacewings, and rove beetles to Family; and carabids to Genus.

Three indicators were used to assess the prevalence and diversity of NE in the pitfall catches: activity density (as an indicator of abundance), species richness, and evenness (Dainese et al. 2019). Activity density was calculated as catch per day by dividing the total number of arthropods in the pitfall trap by the number of days the trap was in the field. Species richness was calculated as the number of unique taxa (at the levels described in the above paragraph) identified in each sample. The evenness of the distribution of taxa in each sample was assessed using the Shannon diversity index, calculated with the *vegan* package (Oksanen et al. 2019) in R (version 3.5.0, R core team, 2018).

4.3.3. Data analysis

Multi-year comparisons between treatments: PI incidence and NE indices

To compare the effect of the spatial and genetic experimental factors on both disease incidence and NE indices across the multiple years of the strip cropping experiments, we used a clustered Wilcoxon rank sum test. This is a conservative non-parametric test suited for comparing two populations of clustered but independent data, which we performed with the *clusrank* package (Jiang 2018) in R. Data were clustered by observation date and experiment block, meaning that we only compared observations for which there were data collected in both the REF and STRIP treatments, and for NE in wheat also in the STRIP_MIX treatment, on the same date and in the same experiment block.

In all clustered Wilcoxon rank sum tests performed, mean ranks of the target indicator, calculated at the experiment block level, were compared between treatments for each cluster. The test can only compare two groups, so we first assessed differences between the REF and STRIP treatments to discern effects of spatial diversity on the target indicator. For disease incidence in potato, this was the only test we conducted, as only REF and STRIP treatments were present at the Lelystad experiment where we had multiple years of *PI* data (2010-2016). With the pitfall catch data, we then conducted a second test comparing the STRIP and STRIP_MIX treatments to assess the potential effect of genetic diversity measures. A significant *p*-value (<0.05) resulting from the test supports the hypothesis that at any given observation moment, the target indicator value in treatment *a* (REF or STRIP) would be significantly different than in treatment *b* (STRIP or STRIP_MIX) for observations conducted in the same experiment block.

Within-year assessment of rate of PI spread, 2017

We analyzed the rate of late blight disease spread in STRIP and STRIP_MIX treatments compared to the REF within a single season and location, 2017 at Wageningen. In this year the experiment set-up included the additional factor of strip width, with two levels (3 m and 6 m). For this analysis we first log-transformed (using the natural logarithm) the disease incidence data, and then calculated the rate of disease spread at the plot level as the difference in disease score between the observation date and the date of the first observed infection. We then used a linear mixed-effects model to test the effect of the treatment factors on those rates (Zuur et al. 2009). In the model we included both spatial (strip width) and genetic (single or mixed cultivar) factors as fixed factors. Experimental plot was nested within field as a random effect in the model to account for potential variability in field conditions. We conducted multiple comparison of means post-hoc tests on the model to make pairwise comparisons between effects of treatment factors on rates of disease spread, with a significant effect determined for *p*-values <0.05. Modelling analyses were conducted using the *lme4* package (Bates et al. 2015) in R, and post-hoc tests were conducted using the *multcomp* package (Hothorn et al. 2008), also in R.

4.4. Results

4.4.1. *PI* in potato

In the multi-year (2010-2016) comparison of *PI* infection scores in the STRIP vs. REF potato treatments at the Lelystad experiment, we found that median *PI* infestation scores were lower for STRIP than for REF in 15 out of 16 paired observation clusters (Fig. 4.4). The clustered Wilcoxon rank sum test of the infection scores in STRIP vs. REF across all years showed the difference to be significant ($p < 0.001$).

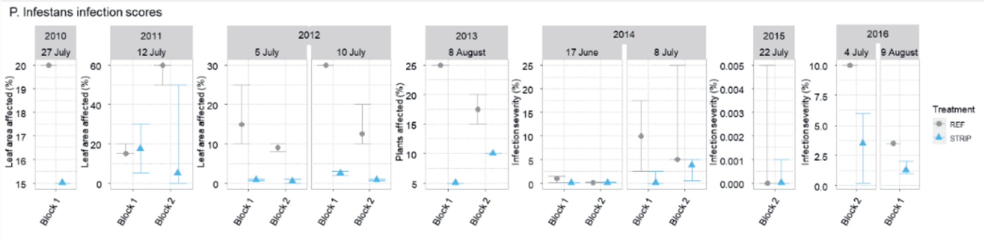

Figure 4.4. PI infection scores in large-scale potato reference fields (REF, grey circles) compared to scores in strips (STRIP, blue triangles) for each observation date across all experiment years (2010-2016) at the Lelystad experiment. Data are paired by cluster (observation date and experiment block). Points show median scores and bars mark minimum and maximum recorded scores for each cluster.

The comparison of plot-level *PI* infection between potato treatments during the 2017 growing season at Wageningen showed a significant effect of both spatial arrangement and cultivar mixing on the rate of disease spread. When the two treatment factors were differentiated as separate fixed factors in the linear mixed model, the post-hoc pairwise comparisons showed that rate of disease spread was significantly lower in the mixed-cultivar treatments (genetic factor) compared to the monocultural REF ($p = 0.0238$), and that only the narrower strip width (3m, spatial factor) showed significantly lower disease spread compared to the REF treatment ($p = 0.0087$). The lowest rates of disease spread were observed when the two treatment factors were combined (Fig. 4.5).

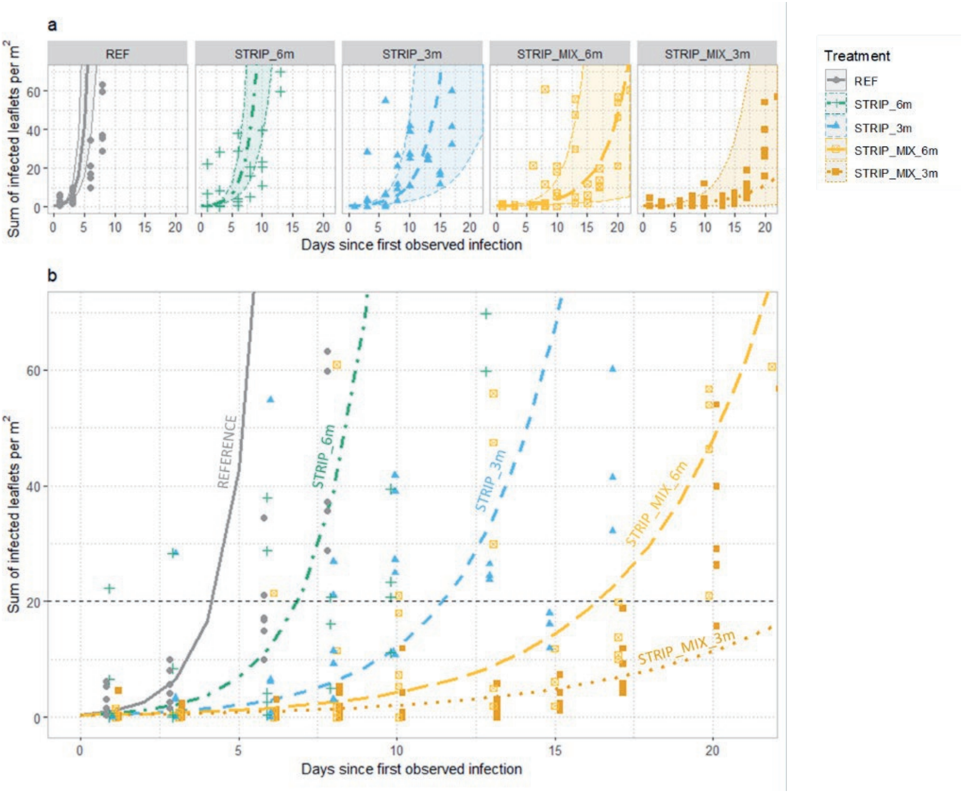

Figure 4.5. PI infection in potato over time during the 2017 growing season at the Wageningen experiment in the five treatments: large-scale reference monoculture (REF, grey circles), single cultivar 6m strips (STRIP_6m, green plus signs), single cultivar 3m strips (STRIP_3m, blue triangles), mixed cultivar 6m strips (STRIP_MIX_6m, yellow boxes), and mixed cultivar 3m strips (STRIP_MIX_3m orange squares). Large bold lines (a and b) show predicted infection per treatment calculated on mean rates modelled with a linear mixed effects model. Shaded transparent ribbons outlined by thinner lines (a) show the standard error of the predicted infection per treatment based on the model. The horizontal black dashed line (b) marks the infection threshold (20 infected leaflets per m^2) at which potato fields must be burned, according to Dutch regulation.

4.4.2. Epigeic natural enemies of aphids in wheat

When analyzed at the level of individual NE groups, we found that across the three years of pitfall trapping in wheat at the Wageningen experiment, there was significantly higher NE activity density (catch per day) in the two strip treatments compared to the REF for all NE groups except *Pterostichus* carabids (Table 4.3, Appendix Fig. A4.2.1). For *Pterostichus,* catches were significantly larger in the REF. The clustered Wilcoxon rank sum test also showed there to be no significant difference in catches between STRIP and STRIP_MIX treatments for any of the NE groups (Table 4.3).

Table 4.3. Effect of spatial and genetic crop diversity on activity density (an indicator of abundance), richness, and evenness of epigeic natural enemies of aphids in wheat collected by pitfall trapping at the Wageningen experiment from 2015-2017. Treatments were compared using a clustered Wilcoxon rank sum test, and data were clustered by observation date and experiment block. Only data for which there were paired observations in both treatments at each sampling date were included in the analysis.

	STRIP vs. REF		STRIP vs. STRIP_MIX	
	p value	effect direction	*p* value	effect direction
Total activity density	0.298	NA	0.846	NA
spiders	< 0.001	STRIP > REF	0.629	NA
rove beetles	< 0.001	STRIP > REF	0.547	NA
harvestmen	< 0.001	STRIP > REF	0.177	NA
carabids (non-*Pterostichus*)	< 0.001	STRIP > REF	0.157	NA
carabids (*Pterostichus*)	< 0.001	REF > STRIP	0.230	NA
other NE	< 0.001	STRIP > REF	0.978	NA
Richness	< 0.001	STRIP > REF	0.402	NA
Evenness (Shannon diversity)	< 0.001	STRIP > REF	0.586	NA

When all NE groups were aggregated, there was no significant difference in activity density between strip treatments and the reference (Table 4.3). Catches in REF on dates when *Pterostichus* carabids were abundant consistently tipped total NE counts above those of the STRIP and STRIP_MIX catches. STRIP and STRIP_MIX had consistently higher diversity index scores across all experiment years (Table 4.3). Compared to the large-scale reference, strips had both a greater number of unique taxa, and more evenness in the distribution of species as indicated by higher Shannon diversity index scores (Fig. 4.6). Added within-strip genetic diversity did not improve NE diversity scores in the STRIP_MIX compared to the STRIP (Table 4.3).

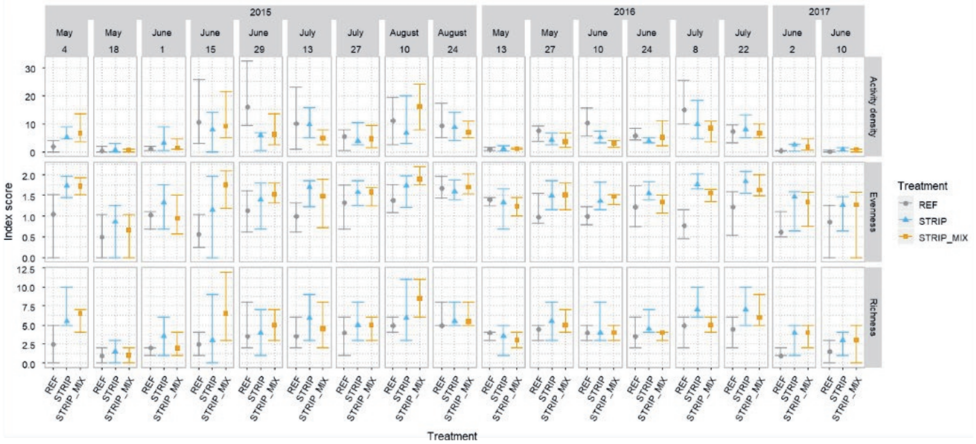

Figure 4.6. Activity density (catch per day, top), species richness (number of unique taxa, middle), and species evenness (Shannon diversity, bottom) of epigeic natural enemies of aphids in wheat collected by pitfall trapping in the three treatments (REF, grey circles; STRIP, blue triangles; STRIP_MIX, orange squares) at the Wageningen experiment for each paired observation date from 2015-2017. Data are presented as clustered by date (medians aggregated across experiment blocks per date) to simplify the figure; in the statistical analysis data were clustered by observation date and experiment block. Points show median scores and bars show the range (minimum and maximum) in catches per cluster.

4.5. Discussion

4.5.1. Stacking diversity: empirical evidence

We hypothesized that stacking multiple diversity dimensions would return increasing benefits in the form of enhanced ecosystem service delivery in arable contexts. With two examples of strip, mixed, and intercropping in the Netherlands, we investigated the effects of activating multiple dimensions of diversity on the delivery of two ecosystem services relevant to Dutch farmers, namely disease mitigation in potato and biocontrol potential in wheat. We found the effect of increasing spatial heterogeneity to be beneficial. Only in the potato case, the combined effect of spatial and genetic diversity measures resulted in the greatest benefit in the form of reduced late blight incidence and slowed disease spread. In the case of biocontrol in wheat, the addition of genetic diversity did not appear to have added value over spatial heterogeneity alone for the measured indicators. We frame our discussion of these empirical findings within the multi-dimensional diversity framework presented in Section 4.2.

PI in potato

The positive effect of spatial diversity on disease mitigation in potato was clearly illustrated in the seven years of experiment data from Lelystad. *PI* infection scores in the STRIP treatment were consistently lower than in the associated large-scale REF fields across all years, a result in accordance with previous studies on spatial diversity and *PI* (Bouws and Finckh 2008; Skelsey et al. 2009; Skelsey et al. 2010). These studies concluded that a combination of physical barrier effects and host dilution were the most likely causes of lower disease incidence in strip-cropped potatoes compared to large-scale monocultures. The physical barrier effect is not a likely explanation for the observed disease mitigation at the Lelystad experiment, since the strips there were planted parallel to the predominant wind direction (contrary to Bouws and Finckh (2008)). Our results imply therefore that by increasing spatial diversity, disease mitigation was obtained through host dilution.

When genetic diversity was added within the potato strip arrangement in the form of cultivar mixtures, we found the additional benefit that the rate of *PI* spread in susceptible plants at the plot level was lowered. The relative rate of disease spread was least in the STRIP_MIX treatments compared to both STRIP and REF plots at Wageningen in 2017, confirming our hypothesis that increased heterogeneity, expressed as the stacking of multiple diversity dimensions, would increase the delivery of the target ecosystem service. The effect of genetic mixing can be explained by the mechanisms at play in spatial diversity, but at plant level rather than crop stand level. Host dilution and barrier effects are both enhanced by the fine resolution mixing of cultivars at the plant level, leading to a greater loss of compatible inoculum in mixtures with contrasting *PI* resistance genes than in pure stands (Andrivon et al. 2003; Skelsey et al. 2005; Skelsey et al. 2009). At Wageningen, it appears that mixing within the strip reduced the likelihood of disease spread at the plant level, while adjacent non-host strips impeded the dispersal of any remaining spores that did propagate, leading to an overall greater reduction in disease severity at the plot level.

Natural enemies of aphids in wheat

Diversification measures that enhance biocontrol potential act from both the bottom up and the top down: by making the cropping system less attractive or less hospitable to pests, and by accommodating predators. The data collected in the strip cropping experiment at Wageningen only allowed us to analyze top-down effects since aphids were not monitored. Our findings reflect several recent comprehensive studies which all show that crop diversity at higher resolutions—whether at the plot, field, or landscape scale—has a positive impact on biodiversity in general and on pest suppression potential specifically (Dainese et al. 2019; Fahrig et al. 2015; Iverson et al. 2014; Lichtenberg et al. 2017; Sirami et al. 2019). However, our results showed the implemented spatial and genetic diversification measures to have differing impacts on top-down pest control mechanisms, and the findings did not support our stacking diversity hypothesis.

In our experiment, the effect of spatial diversity on NE activity density was evident in the significantly larger catches observed in the STRIP treatments compared to the REF for all but one NE group. This result is in line with previous studies which conclude that spatial diversity supports NE populations by providing an array of host, feed, shelter, and habitat sources throughout the cropping season (Ratnadass et al. 2012), as well as refuge during disturbances such as crop cultivation activities (Dassou and Tixier 2016). Only the *Pterostichus* ground beetle was found to be more abundant in the REF system. Although contradictory to Thomas et al. (2006) who found *Pterostichus* to prefer less dense crop stands, our finding is in line with Allema et al. (2019) who showed that *Pterostichus* preferentially occupy large-scale cereal monocultures. While maintaining an abundance of NE is important for top-down aphid control, it has recently been shown that diversity indicators such as species richness and evenness may be more influential predictors of biocontrol potential than abundance (Dainese et al. 2019). Promisingly, our experiment results showed spatial crop diversity had a strong positive impact on both the richness and evenness of the epigeic NE community, a finding that could be explained in part by the work of Allema et al. (2015) who found that different arthropods had preferences for different vegetation types. Diversity of NE presumably also implies a higher likelihood that a mix of specialized and generalist predators are present in the cropping system, which is important for aphid control (Snyder and Ives 2003).

We expected that the addition of increased genetic diversity within the strip arrangement would further improve NE abundance and diversity. However, our experiment results showed no significant difference in NE activity density nor diversity indices between the STRIP and STRIP_MIX systems, indicating that stacking genetic diversity did not add value over what was already achieved via spatial diversification alone. This result is corroborated in a review which found no cases in which mixed intercropping of wheat increased the presence of pest predators (Lopes et al. 2016), however contradicts the 'enemy hypothesis' (Root 1973) and a meta-analysis assessing other crops (Dassou and Tixier 2016). The fact that we did not see added value of genetic mixing within the strip arrangement could imply that at the field scale, the spatial diversity of the strip arrangement had a stronger influence on epigeic arthropod movement patterns than the plant-level genetic heterogeneity of the within-strip crop mixing, as has been found at the landscape scale (Martin et al. 2019).

4.5.2. 3-D Diversity: implications and prospects

Managing complexity

Redefining the agricultural field—that is, changing the way compositions of crops and cultivars are arranged on a farm in space and time—will result in agricultural fields that look different, are more complex, and require new management strategies, technologies, and institutional frameworks. Moving from control-based management towards ecological management positions farmers in a role that is less about managing inputs and outputs and more about facilitating and collaborating with agroecological processes to achieve harvestable yields (Robertson et al. 2014; Storkey et al. 2015; Tittonell et al. 2016). Such a shift could mean that farmers are relieved of selected management burdens as agroecosystems are increasingly able to self-regulate (van Apeldoorn et al. 2011). However, it could also position farmers in a management role that becomes vastly more complex and knowledge-intensive, and potentially expensive (Rosa-Schleich et al. 2019). Before farmers can be expected to engage in such a transition, benefits and drawbacks of a move towards more complexity must be further investigated.

Promisingly, the results of the empirical cases presented here indicate that moderate changes to field design and management can return substantial benefits to farmers in the form of enhanced ecosystem service delivery. In both the potato and wheat examples, introducing spatial diversity alone through strip cropping was sufficient to increase disease suppression and biocontrol potential, respectively. The robustness of the spatial effect implies that farmers can be flexible in how they implement strip cropping, and do not necessarily need special equipment to do so.

At Lelystad, disease mitigation was enhanced despite the arrangement of strips parallel to the dominant wind direction. Additionally, at the Wageningen experiment in 2017, we found that both 3 m and 6 m strip widths showed lower rates of disease spread than the REF. These results indicate that for disease control, strip width can be adapted to fit mechanical capabilities, and strips can be arranged in the field without the constraint of having to be aligned in a particular direction for the benefits to be realized. Further studies on disease spread in relation to strip width and wind direction would be useful for confirming this flexibility.

Although it implies a more complex management approach, namely in terms of post-harvest processing and marketing, the added disease mitigation benefit of introducing genetic diversity within potato strips should not be discounted. Sanitary regulations in the Netherlands require defoliating a potato crop when the severity of a *PI* infestation reaches 7-10% (De Minister van Landbouw 2017). Under organic conditions this is done by mechanical or thermal haulm destruction. A potato stand may produce 700-900 kg of potato fresh weight per hectare per day during the tuber filling stage (Möller et al. 2006), and at defoliation, tuber filling is halted. Delaying the time of defoliation therefore has a strong effect on the quantity and quality (in terms of tuber size) of a potato harvest. Following regulation, the farmer at Wageningen in 2017 defoliated the STRIP_MIX treatment plots two to five days later than the STRIP treatment plots, and higher yields were indeed recorded in the STRIP_MIX plots compared to the STRIP plots (Table 4.1). From a farmer’s perspective, it follows that both delaying the onset of the disease and slowing down its spread—together delaying the termination of the crop—are important objectives in the management of *PI*, and strip cropping offers a robust approach to achieving this.

Given the potential yield benefits of having a potato stand with less late blight infection, one might ask why a farmer would not forgo the mixing of *PI*-resistant with susceptible cultivars and instead just plant strips of the resistant cultivar. This would be simpler by not necessitating post-harvest sorting of cultivars. However, late blight resistance is only one of the criteria that potatoes are bred for (Lammerts van Bueren et al. 2018), and only one trait that farmers weigh when choosing which cultivars to plant. Production potential and consumer preference are also high priorities, both of which tend to be better for the more established non-resistant potato cultivars like Agria. In The Netherlands, the consumer preferences driving potato markets are relatively narrow and traditional, and it can be hard for farmers to sell newer, less well-known varieties like the Carolus or Alouette. Common practice for organic farmers in The Netherlands is therefore to plant some of each in order to reduce the risk of *PI* while also ensuring marketability of the harvest (Pacilly et al. 2019). The experiment in Wageningen reflected these management considerations by taking the susceptible Agria cultivar as the reference.

For biocontrol enhancement, strip-level diversity was found to give as good results as strips combined with plant-level mixing, making the procurement of specialized mixed-cropping machinery appear unnecessary. However, more effective non-chemical aphid control would require the incorporation of design elements that complementarily undermine aphid reproduction and dispersal, in addition to supporting NE populations. Further studies on pest populations in strip arrangements would be useful for helping farmers optimize strip design for biocontrol.

Theoretical considerations

In our discussion of experimental results, we found the conceptual framework for three-dimensional in-field diversity particularly useful for linking management practice outcomes to diversity-mediated mechanisms by discerning which dimensions (spatial or genetic) were activated. The framework does not, however, illustrate nor quantify response relationships between the three diversity dimensions and ecosystem service delivery. Knowing what happens to ecosystem service delivery when multiple dimensions are mobilized in the field at once is necessary for understanding how to manage farm fields for optimizing the delivery of targeted ecosystem services (Bommarco et al. 2013), how to best make use of inherent in-field diversity (Isbell et al. 2017), and thus how much management complexity is required. Once response relationships between field practices and ecosystem service delivery in each dimension are better understood, the diversification space heuristic may be developed to function as a practical solution space from which farmers could select practices to optimize their combined agronomic and ecological goals (Groot et al. 2010; Groot and Rossing 2011).

In our own study, we only examined two dimensions: space and genes. Our brief review of diversity effects, however, implies that adding the third dimension—time—to the strip cropping system could add further value to ecosystem service delivery by breaking pest and disease propagation cycles. Yet our findings on stacking spatial and genetic diversity in wheat may indicate that three-dimensional diversity is not necessary to achieve improved provision of certain ecosystem services. Classic examples in ecology, such as the diversity—productivity response in (natural) grasslands (Hector et al. 1999; Tilman et al. 2001), show that increasing diversity only increases productivity up to a saturation point. Asymptotic yield responses to biodiversity increase have been shown in arable agricultural contexts as well (Barot et al. 2017). There is less consensus on the shape of response curves for other ecosystem services, but in the cases of pest and disease suppression in particular, it is well-known that the magnitude of the diversity effect depends on many additional factors (Bianchi et al. 2006; Isbell et al. 2017; Iverson et al. 2014; Letourneau et al. 2011; Pacilly et al. 2018).

Experimenting with diversification measures at relevant spatial and temporal scales presents challenges to understanding the response relationships between diversity dimensions and ecosystem service delivery. With dispersal distances of 100 m for aphid NE to tens of kilometers for *PI* (Skelsey et al. 2010; Steingröver et al. 2010), variables such as those analyzed here require large-scale reference fields. Due to resource constraints, the large-scale monoculture reference plots used in the presented studies were not replicated and not necessarily in the same field as the strip treatments. Additionally, diversity appears to beget diversity (Reckling et al. 2018); in our spatially and genetically diverse treatments we tended to see more variability in the data than in the large-scale monocultural references. While statistical methods such as those employed in our analysis are able to accommodate incomplete block designs, diversity, and random variation, the practical reality of differences in soil, management history, landscape features, and micro-climate make it difficult to conclude that findings are the sole result of the tested treatments. To reduce uncertainty in studying diverse cropping systems while maintaining practical and scalar relevance, large and long-term experiments are needed, and likely new approaches to experimental design as well.

4.6. Conclusions

Here we explored the concept and implications of three-dimensional diversification of the arable field. We hypothesized that activating diversity in multiple dimensions at once would multiply the ecosystem service benefits, particularly of pest and disease regulation, and tested this hypothesis with two examples of strip, mixed, and intercropping in the Netherlands. Our results showed that spatial diversity alone was enough to increase biocontrol potential in wheat, whereas in the case of late blight in potato, the addition of genetic diversity within the strip did further improve disease mitigation. Based on these cases, we conclude that in-field crop diversity can enhance ecological regulation processes compared to monocultural systems, but that diversifying in multiple dimensions may not always be necessary depending on the targeted services. Compromises between complexity of management and the benefits of increased diversity are achievable, as is the case with strip cropping. This is interesting from a practical perspective, as strip cropping is already possible within current agronomic and mechanical constraints, requiring some adjustments to field conceptualization and management but not a full technological shift. If more positive response relationships are proven between stacked diversity dimensions and ecosystem service delivery, a move towards greater complexity (e.g. pixel cropping) could be a next step in the transition towards a more ecologically sound and productive model for redefining industrialized arable fields.

Acknowledgements

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Appendix 4

A4.1. Experiment layouts

Field Lab for Agroecology and Technology, Lelystad, NL

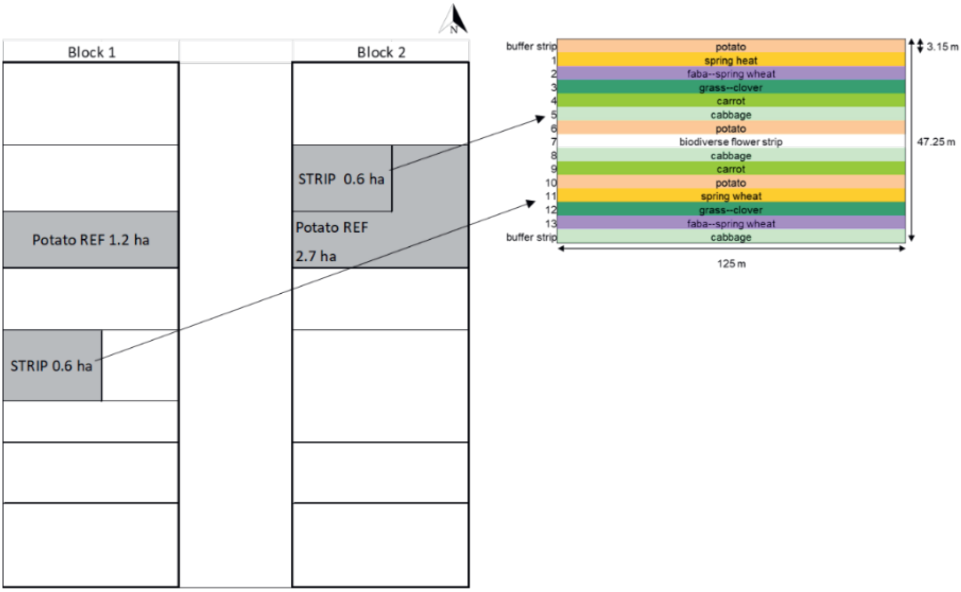
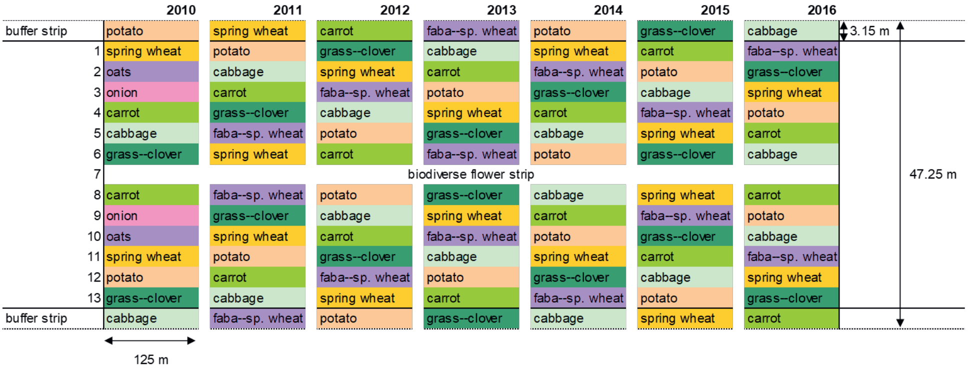


Figure A4.1.1. Location of the strip and reference plots at the Field Lab for Agroecology and Technology in Lelystad (not to scale). Detail shows the strip arrangement within the STRIP treatment plot. Location of STRIP plots remained fixed throughout experiment years, REF plots rotated; map shows the layout in 2014.



	2010	2011	2012	2013	2014	2015	2016
buffer strip	potato	spring wheat	carrot	faba--sp. wheat	potato	grass--clover	cabbage
1	spring wheat	potato	grass--clover	cabbage	spring wheat	carrot	faba--sp. wheat
2	oats	cabbage	spring wheat	carrot	faba--sp. wheat	potato	grass--clover
3	onion	carrot	faba--sp. wheat	potato	grass--clover	cabbage	spring wheat
4	carrot	grass--clover	cabbage	spring wheat	carrot	faba--sp. wheat	potato
5	cabbage	faba--sp. wheat	potato	grass--clover	cabbage	spring wheat	carrot
6	grass--clover	spring wheat	carrot	faba--sp. wheat	potato	grass--clover	cabbage
7	biodiverse flower strip						
8	carrot	faba--sp. wheat	potato	grass--clover	cabbage	spring wheat	carrot
9	onion	grass--clover	cabbage	spring wheat	carrot	faba--sp. wheat	potato
10	oats	spring wheat	carrot	faba--sp. wheat	potato	grass--clover	cabbage
11	spring wheat	potato	grass--clover	cabbage	spring wheat	carrot	faba--sp. wheat
12	potato	carrot	faba--sp. wheat	potato	grass--clover	cabbage	spring wheat
13	grass--clover	cabbage	spring wheat	carrot	faba--sp. wheat	potato	grass--clover
buffer strip	cabbage	faba--sp. wheat	potato	grass--clover	cabbage	spring wheat	carrot

Figure A4.1.2. Experimental layout and crop rotation in the strip treatments at the Field Lab for Agroecology and Technology in Lelystad, NL from 2010-2016 (not to scale). Schematic shows one experiment block; the full experiment consisted of two replicated blocks each following the same scheme.

Droevendaal Experimental Farm, Wageningen, NL

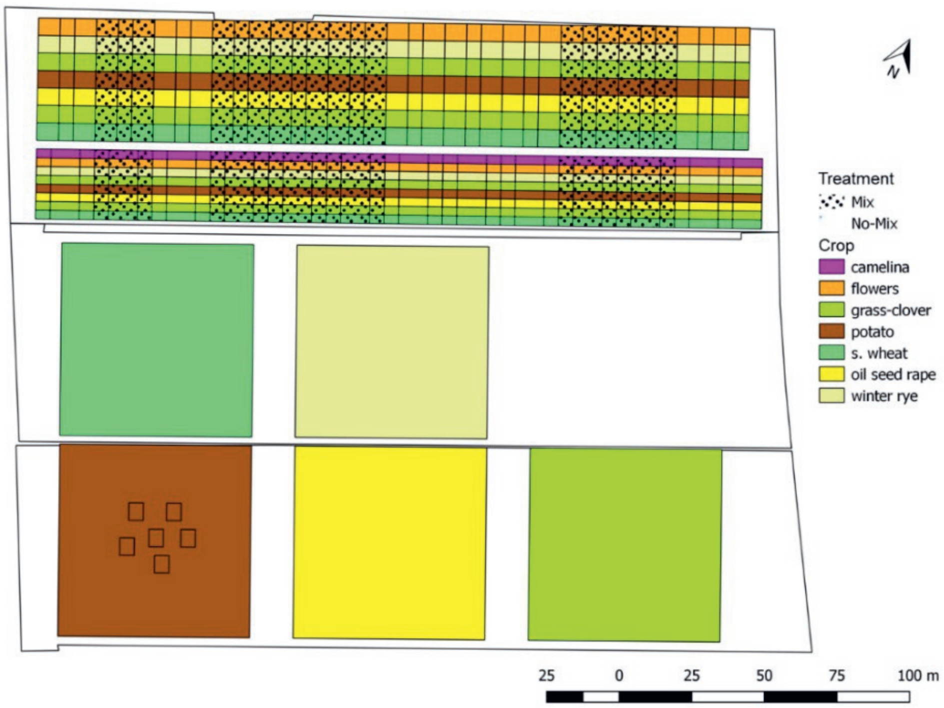


Figure A4.1.3. Field layout of the strip cropping experiment located at Droevendaal Experimental Farm in Wageningen, The Netherlands. Map shows the crops sown in the 2017 growing season.

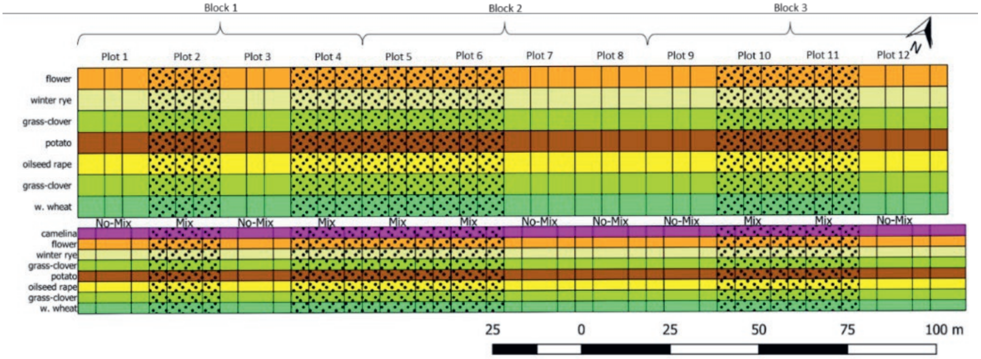


Figure A4.1.4. Detailed layout of the strip treatments in the strip cropping experiment located at Droevendaal Experimental Farm in Wageningen, NL. Map shows the crops sown in the 2017 growing season.

A4.2. Pitfall catches per natural enemy group

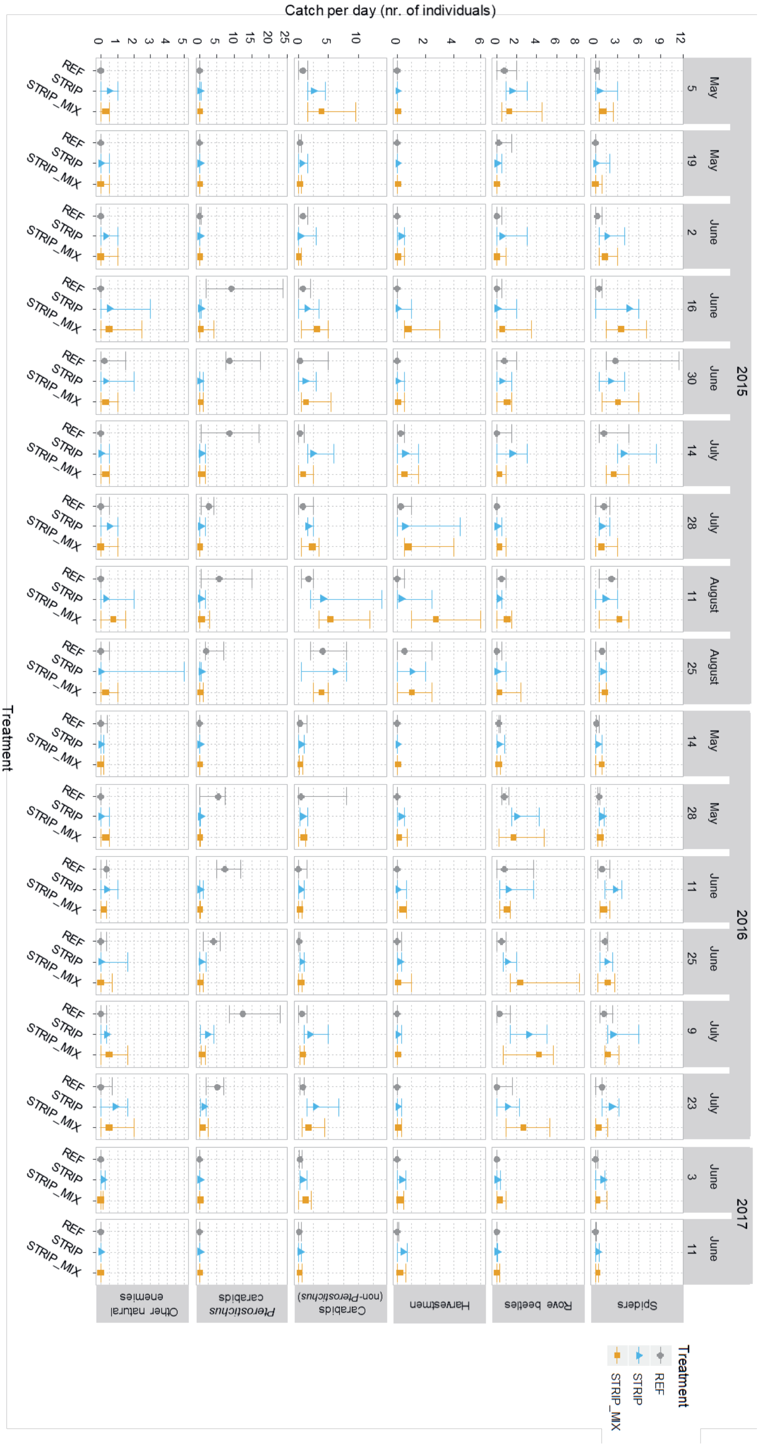


Figure A4.2.1. Activity density (catch per day) of epigeic natural enemy groups in wheat collected by pitfall trapping in the three treatments (REF, grey circles; STRIP, blue triangles; STRIP_MIX, orange squares) at the Wageningen experiment from 2015-2017. Data are presented as clustered by date (medians aggregated across experiment blocks per date) to simplify the figure; in the statistical analysis data were clustered by observation date and experiment block. Points show median scores and bars show the range (minimum and maximum) in catches per cluster.

Chapter 5

Prospects for increasing the resolution of crop diversity for agroecosystem service delivery in a Dutch arable system

This chapter is under revision at *Agriculture, Ecosystems, and Environment* as:

Ditzler, L., Rossing, W. A. H., Schulte, R. P. O., Hageman, J., & van Apeldoorn, D. F. Prospects for increasing the resolution of crop diversity for agroecosystem service delivery in a Dutch arable system.

Abstract

Diversifying open-field cropping systems is a promising option for increasing the agroecosystem service (AES) delivery capacity of arable farms. Past research has shown that more diversity can be better for AES delivery but also implies greater management complexity, so finding a balance between agroecological benefits and management demands is important. In this study we developed a scoring system for quantifying the structural diversity of cropping systems, and applied it to the analysis of a three-year field study in The Netherlands where we tested multiple diversity treatments. Our aim was to find an optimal resolution of diversity within the study context. Treatments included strip cropping (3 m x 54 m strips sown in adjacent crop pairs) and pixel cropping (0.25 m^2 plots each sown with one of six crops and arranged in 7.5 m x 12 m grids). We used multiple AES indicators (soil fertility, crop yield and quality, weed cover and diversity, and natural enemy activity density) to assess the performance of each treatment in three focal crops (cabbage, wheat, and potato). We analyzed response relationships between treatments, diversity scores, and AES indicators, and assessed the contribution of diversity in space, time, and genes to AES delivery in each crop. We found no clear indication that one treatment performed better than the rest across AES indicators; there was substantial variation between crops and AES indicators within treatments. In the diversity scores analysis we observed robust positive effects of increasing diversity on wheat grain protein, weeds species diversity, and natural enemy activity density. Significant negative effects of increasing diversity on cabbage and potato yields and quality and weed cover were only present when the pixel treatment data were included. We found no clear effect of individual diversity dimensions on AES delivery. Our findings suggest that in the study context, higher resolution in-field diversity can be beneficial for the ecological aims of associated biodiversity and biocontrol potential. Agronomic indicators were either neutral, varied per crop, or reached a limit at a resolution of diversity equated with the most diverse strip cropping treatment, suggesting a tipping point when moving from strip to pixel layouts. The prospects for strip cropping thus appear better than for pixel cropping in terms of balancing production with increases in other AES while also maintaining management feasibility.

Keywords: Strip cropping, pixel cropping, structural diversity, three-dimensional diversity, field crops

5.1. Introduction

In the context of arable and broad-acre cropping systems, ‘diversification’ implies a move from a simplified system state (e.g. a homogeneously planted field of a sole crop, which we refer to here as a ‘monoculture’) towards something more complex through the introduction of heterogeneity (Hufnagel et al. 2020). This heterogeneity may come in the form of additional crops variably arranged in space and time. Diversification is frequently centered in farming systems research as a viable approach to mitigate (or even remediate) the ecological damage incurred by monocultural production systems, and understandably so—the scientific evidence in favor of diversification is increasingly conclusive. Recent meta-analyses have shown that diversification of cropping systems at both the field and landscape scale can be linked to the increased provision of a wide range of agroecosystem services (AES) (Beillouin et al. 2021; Tamburini et al. 2020). Localized examples show that AES provision sometimes comes with trade-offs such as yield penalties (Botzas-Coluni et al. 2021; Egli et al. 2021), but the study by Tamburini et al. (2020) concludes that trade-offs are not inevitable.

Research tends to show that higher resolutions of field-scale diversity are more favorable for AES delivery (Fahrig et al. 2015; Sirami et al. 2019; van Oort et al. 2020), but translating these findings into practice in intensive industrialized contexts where ecological sustainability gains are most needed, such as in European arable cropping systems, implies substantial changes to the way arable fields are designed and managed. Following the assumption that diversity at higher resolutions will bring greater benefits, a re-design of arable farming towards greater diversity will require a rethinking of how to approach the notion of the farm field and will probably involve a substantial increase in the resolution of discrete management units within the field (Ditzler et al. 2021b). As management units become smaller, the ecological and agronomic complexity of the farm field will amplify, with the challenge of implementation falling first on farmers.

European farmers themselves have already flagged management complexity and a lack of corresponding technical solutions as barriers to adopting diversification practices (Morel et al. 2020; Rodriguez et al. 2021). As farmers take on the challenge of diversifying their systems in order to meet national and regional sustainability targets (EC 2020), a pressing question is then how much in-field heterogeneity is optimal within a given set of resources, constraints, and objectives. Where is the operational balance between gleaning the ecological benefits of diversification, achieving production aims, and maintaining management feasibility? Determining this balance will require a more thorough understanding of context-specific relationships between diversification practices and AES delivery, and of the role of management in driving this relationship.

Diversifying a monocultural cropping system at the field level (that is, not taking into account field margins, hedge rows, semi-natural habitat elements, etc., which have their own role in providing AES) can be achieved through a range of practices which offer a farmer the opportunity to select locally appropriate options. In a preceding paper, we proposed a framework for classifying these options by conceptualizing in-field diversification as occupying a three-dimensional space framed by the axes temporal, spatial, and genetic diversity (Ditzler et al. 2021b). We posited that any practice of cropping system diversification can be classified as activating one or more of these dimensions. To illustrate this, we positioned example production systems within the three-dimensional space by assigning theoretical scores on a unitless scale (from 'less' to 'more' heterogeneous) in each dimension. This descriptive and heuristic exercise is particularly useful for unraveling which dimensions are activated (i.e. what could be considered the *structure* of the diversity) when a farmer implements different practices.

The more impactful prospective function of the framework would be to facilitate anticipating the potential impacts (agronomic, ecological, management related) of implementing multi-dimensional in-field diversity. This would allow farmers, advisors, and researchers to choose practices matching their unique constraints and objectives based on ex-ante assessment, and policy makers to direct compensation or subsidies based on a farm's diversity level. To make this step would require incorporating into the framework a qualification of the function of each dimension of diversity (Keichinger et al. 2021). There are some general principles which may be gleaned from the literature as to what agroecosystem mechanisms and services are likely associated with each temporal, spatial, and genetic diversity (Stomph et al. 2020; Ditzler et al. 2021b). For example, temporal diversity is often associated with breaking disease transmission cycles (Leoni et al. 2015), spatial diversity with increasing crop yields (Li et al. 2020), and genetic diversity with increased resource use efficiency (Hauggaard-Nielsen et al. 2008) and biocontrol of pests (Iverson et al. 2014). However, more knowledge on these relationships is needed in order to determine what the optimal resolutions and combinations of diversity dimensions might be within a given context.

A first application of the three-dimensional diversity framework to the analysis of strip cropping experiments in The Netherlands illustrated the potential for the best options to diverge depending on the desired outcomes. In one case (disease control in potato), the more diverse cropping system did indeed deliver more benefits, but in another case (biocontrol potential in wheat) increased diversity only improved the targeted agroecological aims up to a point after which higher-resolution diversity no longer added observable value (Ditzler et al. 2021b). These findings highlight the importance of gaining further insights into how far down the complexity continuum the benefits of a particular diversity dimension extend, and under what conditions diversity at higher resolutions (and the associated management complexity) may be warranted to achieve sustainability aims.

Box 1. Strip vs. pixel cropping

Strip cropping is the practice of growing two or more crops in alternating multi-row strips wide enough to cultivate independently but narrow enough to allow for ecological interaction. Within a strip, additional diversity measures can be 'stacked' (e.g. relay cropping or crop mixtures within the strip layout). Among the many options for diversifying arable fields, strip cropping is particularly interesting because it mobilizes the infrequently utilized spatial dimension of diversity but does so from inside the framework of widely adopted cultivation methods (Ditzler *et al.*, 2021b). Despite its accessibility and some strong evidence in favor of its potential (Bouws and Finckh, 2008; Ditzler et al., 2021b; Juventia et al., 2021; Yu et al., 2015), strip cropping remains a niche production method in Europe.

Strip-cropped field in Wageningen, 2021 (photo: L. Ditzler)

Pixel cropping (sometimes referred to as *pixel farming*) is a nascent open-field farming method which utilizes three-dimensional crop diversity at higher resolutions than can be achieved with strip cropping (Ditzler and van Apeldoorn, 2018). Rather than row-based cultivation (a familiar trope maintained in strip cropping), pixel cropping splits the field into a grided pattern planted with small patches ('pixels') of multiple different food and service crops. In these assemblages, the crop—crop interface increases from two edges (as in strip cropping) to four, thereby multiplying the potential for ecological interaction between neighboring crops (Ditzler, 2020). Pixel cropping can be understood as a prototype or proxy for a wider range of future-oriented, high-resolution diversification practices which are possible to imagine when drawing on polyculture techniques practiced globally (e.g. Rodríguez-Robayo *et al.*, 2020).

Pixel-cropped field in Wageningen, 2020 (photo: L. Ditzler)

The primary aims of this research were 1) to gain further insight into what might be the resolution of diversity at which AES delivery is greatest within a particular context (here, an organic, arable cropping system in The Netherlands), and 2) to better understand the influence of each diversity dimension (space, time, genes) in achieving desirable agroecological outcomes. To approach these aims, we extend the functionality of the three-dimensional diversification heuristic proposed by Ditzler et al. (2021b) and use it as a tool in our analysis. We extend the framework by assigning meaningful values to the diversity dimension axes, and present a simple approach for devising these values—here forward referred to as 'diversity scores'. We then utilize the scores in the analysis of empirical data collected in a long-term crop diversification experiment in The Netherlands. Keeping in mind the testimonies of European farmers which teach that some diversification practices are more accessible, more locally appropriate, and more easily embedded into existing production chains than others (Morel et al. 2020), the experiment tested a spectrum of diversification options which range from currently feasible (strip cropping) to future oriented (pixel cropping) (see Box 1 for descriptions of these practices). Also keeping in mind the demand for multi-functionality that sustainability targets place on the design of (future) farming systems (EC 2020), we assess a range of performance indicators which capture provisioning as well as regulating and biodiversity-related AES (Duru et al. 2015b; Zhang et al. 2007). Management aspects in the operationalizing of multi-dimensional diversity (e.g. decision making processes, machine requirements, time spent on cultivation tasks) were not assessed quantitatively in this study. However, we bring several years of qualitative observations and experience with the tested diversification practices and we draw on this experience in the discussion to bring light to the issue of management complexity and what challenges and trade-offs might exist there.

5.2. Materials and methods

5.2.1. Experiment site and design

We conducted this research in a long-term systems experiment at the Droevendaal Organic Experimental and Training Farm in Wageningen (51°59'27.4"N, 5°39'36.0"E), The Netherlands. We collected data for three full growing seasons, from March 2018 until November 2020, and a final soil survey was conducted in March 2021. Soil at Droevendaal is sandy, and the average annual rainfall for the area is 780 mm with an average daily temperature of 9.4°C. There were some weather anomalies during the study period, notably an uncharacteristically hot and dry summer in 2018, and a very dry spring in 2020 (see Appendix A5.1 for weather data during the study period).

The experiment was designed to test a gradient of crop diversification methods of increasing complexity: monocultural reference plots, narrow strips of various complexity, and a pixel cropping layout (Fig. 5.1). Crops were selected for their relevance to Dutch organic farmers and suitability for local soil conditions, and strips and treatment blocks were sized to operational scales relevant to farmers' practice. In the strip treatments, crops were planted in pairs selected for their mechanical compatibility and potential for ecological synergy. Crops and pairs changed slightly from year to year after some crop failures required adjusting the composition of the rotation. In this study we analyze the two crop pairs that remained consistent throughout the study years: white cabbage (*Brassica oleracea* L. var *capitata*) paired with wheat (*Triticum aestivum* L.), and potato (*Solanum tubersosum* L.) paired with grass (*Lolium multiforum* L.).

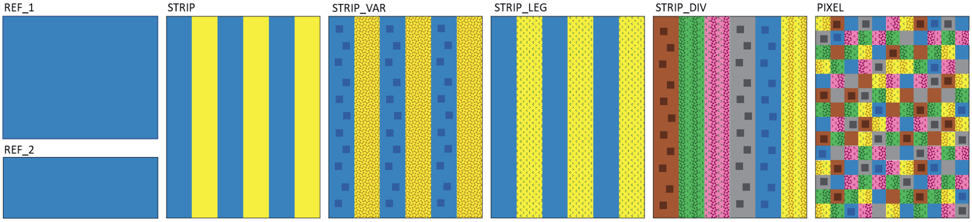


Figure 5.1. Diagrammatic representation of experimental treatments employed at the Droevendaal experiment, here illustrated for the focal crop cabbage (blue) and its pair wheat (yellow). Large-scale references (REF_1 and REF_2) were present in the field for all focal crops grown in strips. Not to scale. See the text body for explanation of the treatments.

Strips were 40-60 m long and 3 m wide. The strip treatments included: sole-cropped, single variety strips (STRIP); mixed variety strips (STRIP_VAR) in which multiple varieties of the crop utilized in the STRIP treatment were mixed in a replacement design (two varieties in cabbage, wheat, and grass, three varieties in potato); legume-added strips (STRIP_LEG) in which a legume was sown in an additive design into the crop utilized in the STRIP treatment in one crop of the pair (faba bean (*Vicia faba* L.) in wheat and red clover (*Trifolium pratense* L.) in grass); and high-diversity strips (STRIP_DIV) with the varieties from STRIP_VAR and the legumes from STRIP_LEG sown together. STRIP, STRIP_VAR, and STRIP_LEG treatments were planted in repeating crop pairs, and the STRIP_DIV treatment was planted in a block with all crop pairs in the rotation adjacent to one another (Fig. 5.1). In 2018, STRIP_DIV was not present and instead three separate treatments were utilized, DIV_STRIP, DIV_VAR, and DIV_LEG, in which the same crop composition utilized in STRIP, STRIP_VAR, and STRIP_LEG, respectively, were planted in a block with all crop pairs in the rotation adjacent to one another.

The PIXEL treatment was applied in two 7.5 m x 12 m plots in which crops were allocated to 0.5 m x 0.5 m squares ('pixels') planted with the same high-diversity mix of crop varieties and legumes utilized in the STRIP_DIV treatment. Crops were randomly allocated in equal proportion throughout the plots in the first year, and subsequently each pixel followed the crop rotation.

Reference plots (REF_1 and REF_2) were planted with the same crops and varieties as in the STRIP treatment. REF_1 consisted of large-scale monocultural plots (~0.4-0.6 ha) and REF_2 consisted of smaller-scale (~135 m^2) monocultural plots.

The fields including the strip treatments and REF_2 plots were laid out in a randomized complete block design with three replicates; this layout, including the location of the two PIXEL plots, remained fixed throughout the study years. Due to their size, REF_1 plots were moved within the farm from year to year as space allowed and therefore were not always in the same field as the rest of the treatments. The REF_1 plots did not necessarily follow the same crop rotation, and were not replicated. Therefore, each REF_1 plot was accompanied by several adjacent STRIP treatment strips to create a connected incomplete block design and allow for possible field effects to be captured in statistical analyses. A field map of the experiment layout is provided in Appendix A5.2.

The experiment was managed according to Dutch organic regulations (Skal 2020), and all strips and pixels followed a crop rotation standard for the region (cabbage—barley—potato—wheat—pumpkin—grass(/clover)). The sowing density of the main crop was consistent across all treatments and references. Reference plots and strip treatments were cultivated using standard tractor-driven farm machinery. The pixel plots were cultivated by hand with best efforts to mimic the method and timing of cultivation tasks carried out in the reference and strip treatments with one notable difference in weeding: pixel plots were selectively hand-weeded, removing only the largest and most competitive species. All treatments received manure fertilizer except those including legumes, which received only plant-based fertilizers. Further treatment details including cultivars and fertilization regimes are given in Appendix A5.3.

5.2.2. Data collection

We measured indicators relevant to AES delivery in four categories: soil fertility, crop production, weed control, and biocontrol potential (Table 5.1). These were selected to encompass a range of potential crop diversification impacts relevant to farmers and society, and to address research gaps previously identified in the review by Ditzler et al. (2021a). All data were collected following general sampling rules applied consistently across years. Sampling from strips at the outer edge of a treatment block (i.e. buffer strips, those sharing a border with the neighboring treatment block) was avoided, and whenever possible a 10 m buffer from each strip end was excluded from the sampling area to avoid edge effects. The 10 m buffer did not apply to crop harvest data, rather the harvest of the entire strip was recorded. Data from the two pixel plots were collected whenever possible on a per-pixel basis, and otherwise aggregated per plot. REF_1 plots were sampled from the middle of the area, excluding a 10 m buffer from each plot edge. REF_2 blocks were sampled from the middle 3 m strip of the block. Not all indicators could be measured for each crop, every year; we account for this in our statistical analyses (see Section 5.2.4). Methods of collecting data for each indicator are described in the following subsections.

Table 5.1. Indicators assessed in the field experiment as measures of agroecosystem service (AES) delivery.

Agroecosystem service category	Indicator	Units	Crops
Soil fertility	Plant-available nitrogen	kg mineral N ha^{-1}	Cabbage, wheat, potato, grass
	Soil organic matter content	Percent SOM (%)	Cabbage, wheat, potato, grass
Crop production	Fresh yield	kg m^{-2}	Cabbage, wheat, potato
	Crop quality	Fresh marketable weight cabbage head (kg)	Cabbage
	Crop quality	Proportion yield marketable (0-1)	Cabbage, potato
	Crop quality	Thousand kernel weight (g)	Wheat
	Crop quality	Grain protein content (%)	Wheat
Weed control	Weed pressure	Total cover by weeds (%)	Wheat
	Weed species diversity	Species richness	Wheat
	Weed species diversity	Shannon index	Wheat
Biocontrol potential	Beneficial epigeic arthropod abundance	NE activity density (total catch of four arthropod taxa per 5-day trapping event (i.e. sample round))	Cabbage, wheat, potato, grass

Soil fertility parameters

Two soil fertility parameters—plant available nitrogen (N) and soil organic matter (SOM) were measured in March 2018 and March 2021. The timing of the soil sampling was chosen for its relevance to farmers: sampling done in early spring is generally the main indicator farmers use in order to determine how much to fertilize their fields prior to planting the season's first crops. Soil samples were collected at 0-25 cm soil depth (8 replicates in REF_2 and 18 replicates in strips per crop pair/treatment in 2018, and 6 replicates per crop pair/treatment in 2021). Samples were stored at 5° C until preparation for analysis, and then oven-dried at 70° C for 48 hours. Dried samples were ground and sifted to 2 mm. Nitrate (NO_3^-) and ammonia (NH_4^+) contents of the dried soil samples were determined using a segmented-flow system (Skalar San++ Continuous Flow Analyzer) following Houba et al. (2000) and available N was then calculated on a kilogram per hectare basis using bulk density values obtained in the same field in March

2018. Organic matter content (%) of dried soil samples was measured through loss on ignition (Ball 1964).

Production indicators

Crops were harvested each year at the time the farmers deemed appropriate. In the reference monocultures yields were recorded in 3-meter strip widths and in the strip treatments yields were recorded either per strip, half strip, or crop row. This resulted in six whole strips sampled per crop per treatment per year, with the exception of STRIP_DIV for which there were three replicates per crop per year and PIXEL. Crops in the PIXEL treatment were harvested and recorded per pixel or aggregated by plot depending on the crop and year. Cabbage and potato yields were measured and recorded in the field immediately following harvest. Wheat was threshed and stored after harvest in a drying facility until moisture content reached approximately 12-15% and then weighed. All crop yields are reported as fresh weights (kg per m^2). Grass was mulched and returned to the field and therefore grass yields were not measured.

Cabbage and potato quality were assessed as the proportion of marketable produce within a subsample of the harvest. Eight cabbage heads were randomly selected per harvested area (per strip, pixel plot, or reference plot) during harvest. Marketability was determined by measuring the fresh marketable weight (kg) of individual cabbage heads after removing wrapper leaves damaged by herbivore feeding. Following Juventia et al. (2021), cabbages under 0.4 kg were considered unmarketable. For potato, subsamples of approximately 10 kg were taken from the harvested area and sorted by size. Following Dutch market standards, potatoes < 35 mm and > 65 mm in diameter were considered unmarketable.

Wheat quality was assessed using two parameters: thousand kernel weight (TKW) and grain protein content. After fresh yield was recorded, a subsample of each wheat harvest sample was dried at 70° C for 48 hours and the grains were cleaned. The weight (g) of 1000 cleaned grains was recorded, and then the subsample was ground to 2 mm and analyzed in the laboratory to obtain the percent total N content of the grain (Houba et al. 2000). Grain protein content (%) was estimated as the percent total N multiplied by 5.7 following Sosulski and Imafidon (1990).

Weed cover and diversity

Weed cover and weed species diversity were assessed in the wheat crop in June 2019 and June 2020. To determine weed cover, a 0.5 m x 0.5 m quadrant was placed at six random locations per strip treatment block and reference plot (6 pseudo-replicates per treatment). Within each quadrant, the percentage of absolute soil cover by weeds was estimated (Hanzlik and Gerowitt 2016). In each sampling area used for the weed cover assessment, weed species were recorded and their densities estimated along a transect in the middle of the area using the method and density classification scale described by Gerowitt and Hofmeijer (2018). These data were used to determine the species richness (number of species) and Shannon diversity index (a measure of species richness and evenness, Spellerberg and Fedor (2003)) for each transect, which we calculated in R (version 3.6.0, R core team, 2020) with the *vegan* package (Oksanen et al. 2019).

Beneficial epigeic arthropods

We assessed the activity density of beneficial epigeic arthropods as an indicator of biocontrol potential. Arthropods were captured using pitfall trapping in all treatments and crops two times per year (June/July and August/September) in 2018, 2019, and 2020. See Ditzler et al. (2021b) for an explanation of the pitfall trapping method employed. In the STRIP, STRIP_VAR, and STRIP_LEG treatments, one pitfall trap was placed in each of two strips per treatment/block per trapping event (n = 6 per crop per treatment). One pitfall was placed in each of the STRIP_DIV, DIV_STRIP, DIV_VAR, and DIV_LEG strips in each block (n = 3 per trapping event). The PIXEL treatment contained 1 or 2 pitfall traps per plot per trapping event. In REF_1, pitfalls were placed inside the 10 m buffer at random locations (n = 3 per trapping event in 2018, n = 6 in 2019 and 2020). Arthropods captured in the pitfall traps were preserved in 70% ethanol and four known taxa of beneficial arthropods (crop pest and weed seed predators) were identified and counted per trap: spiders (*Araneae*), harvestmen (*Opiliones*), adult and larval carabids (*Carabidae*), and adult and larval rove beetles (*Staphylinidae*). The catch of these four groups was summed per trap per trapping event to give the total catch per trap, an indicator of activity density.

5.2.3. Diversity scoring system

In the three-dimensional diversity heuristic presented by (Ditzler et al. 2021b), cropping systems are scored as having relatively ‘more’ or ‘less’ diversity in each dimension (time, space, genes) on a unitless scale. To extend this framework and make it suitable for applications with empirical data, we devised a simple system for calculating actual scores on each axis for real-life cropping systems. This system is inspired by an approach proposed by Keichinger et al. (2021). Following the practice in landscape ecology which characterizes diversity as a factor of both landscape composition and configuration (Fahrig et al. 2011), the scoring system is designed to quantify what is in the field (i.e. how many discrete components there are), what the resolution of those components is, and how they are arranged in space and time. We applied our scoring system to generate a time, space, genes, and compound diversity score for each crop—treatment combination present in the field data (Appendix A5.4) and used these scores as predictor variables in our statistical analyses.

In the scoring system, each diversity dimension receives a score which is composed of two indicators. A precedent for assessing complexity at the landscape scale has been set in the literature, but methods for quantifying the heterogeneity of production systems at field-scale are less common. Thus, to select the indicators composing each dimension score we drew on metrics commonly used in landscape ecology and made adaptations to suit field-scale applications. We tested various indicators for their applicability and possible correlation before selecting the two final indicators: number of growing periods and return frequency (time dimension); edge density and shape index (space dimension); patch species richness and neighbor species richness (genes dimension). Table 5.2 gives an overview of how these indicators were defined and calculated. The two indicators for each dimension are summed and then scaled from 0-1 to give a time score, space score, and genes score. The three scaled dimension scores can then be summed to create a compound diversity score with a possible range from zero (less diverse) to three (more diverse).

We calculated diversity dimension scores at the crop patch level. We here define a crop patch as a homogenous space—time management unit (i.e. one plot, strip, or pixel) for a given focal crop. Indicators in the time and genes scores are calculated to also include the 'neighborhood' of the crop patch within a 9 m radius. This distance was chosen as the inclusion zone because it captures the arrangement of strip pairs (which we deem important to the performance of strip cropping systems) as well as the full range of diversity present in the most diverse treatment we analyzed here, while remaining within the boundaries of the experimental fields. For other applications of this scoring method, and depending on the indicators being assessed, a different radius may be logical, as it has been shown that different organisms and ecosystem processes may only be active or evident at certain spatial scales (Botzas-Coluni et al. 2021; Steffan-Dewenter et al. 2002).

Table 5.2. Indicators comprising the temporal, spatial, and genetic diversity scores used to extend the framework proposed by Ditzler et al. (2021b). Each dimensional score is scaled from 0-1 and can then be summed to generate a compound diversity score for each system being analyzed. Scores are assigned at the crop patch level.

	Indicator	Calculation	Notes / interpretation
Time score	Number of unique growing periods	The number of unique growing periods within one calendar year. Calculated including the focal patch and the neighborhood within a 9 m radius of the center of the focal patch.	Indicator is calculated using a sowing and harvesting calendar. For example, in a strip pair configuration sown and harvested in a relay planting schedule and then followed by a green manure, the score would be 5: a period of fallow, a period of crop *a* growing alone, a period of crop *a* and *b* growing simultaneously, a period of crop *b* growing alone, and a period of green manure.

	Return Frequency (RF)	RF = 1 – (frequency in rotation / years in rotation)	Frequency in rotation is considered here as the number of returns of the crop patch to the same field over the course of the rotation. This implies that e.g. in a 6-year crop rotation composed of crop pairs grown in strips, the same crop will return to the same field (to a strip adjacent to where it was last) twice, i.e. every three years, and RF=1-2/6=2/3.
Space score	Edge Density (ED)	ED = p / a p = length of patch perimeter (m) a = patch area (m^2)	Indicator of the size and shape of a patch. Reference: McGarigal et al. (2012).
	Shape Index (SI)	SI = (0.25 * p) / √ (a) p = length of patch perimeter (m) a = patch area (m^2)	An indicator of the complexity of patch shape compared to a square of the same size. SI = 1 when the patch is square and increases without limit as patch shape becomes more irregular. Reference: McGarigal et al. (2012).
Genes score	Patch Crop Richness	The number of sown species and varieties in the focal patch	Reference: Juventia et al. (2021).
	Neighbor Species Richness	The number of neighboring species and varieties within a 9 m radius of the center of the focal patch	

Since it was an aim of our analysis to unravel relationships between diversity dimensions and AES delivery, the scoring system was designed to capture the structural features of each diversity dimension in time and space which a farmer can manipulate through field management, but not to qualify the functions of the diversity. To that end, and in contrast to the approach used by Keichinger et al. (2021), we do not apply weighting to the time, space, or genes component scores in order to avoid embedding qualifications regarding the relative importance of one indicator or dimension over another. Additionally, because each dimension score is scaled to the range present in the cropping systems being assessed, it should be noted that scores quantify diversity relative to the least and most diverse system being analyzed (here the large-scale reference monocultures and the pixel cropping treatment, respectively) and are therefore not universal standards.

5.2.4. Statistical analysis

All data processing, analyses, and visualizations were performed in the R environment (R core team, 2020). We conducted two types of analysis: i) we assessed the response of individual AES indicators to treatment and diversity scores using linear modelling, and ii) we assessed relationships between diversity dimensions and the AES indicators simultaneously using multivariate analysis. Before analysis, data were checked for outliers using visual assessment and with the R package *outliers* (Komsta 2011). From within the set of outliers identified, only those that appeared agronomically very unlikely (probable data collection errors) were removed. In all analyses, we used REF_1 as the default sole-crop reference for production indicators and natural enemy assessments. We used REF_2 as the reference for soil and weeds analyses, and when REF_1 was missing from the data. If both references were in the data, we report both.

We assessed the response of each AES indicator separately using linear mixed-effects models. First, we used treatment as the predictor variable; in this analysis we excluded the treatments DIV_STRIP, DIV_VAR, and DIV_LEG because they were only present in one year. Next, we used the compound diversity score as the predictor variable and included data from all treatments. Before modelling, each dataset was checked for assumptions of normality using visual and statistical checks on residuals (Zuur et al. 2009) and transformations (log- or square-based) were applied if normality assumptions were not met. In each model, the predictor variable (treatment or diversity score) was set as a fixed effect, and a combination of year, field, and treatment block were included as random effects with block nested within field. For soil data year was included as an additional fixed effect, and for arthropod data sampling round and crop pair were included as additional fixed effects. Interactions between fixed effects were tested and included in the model when found to be significant. Models were built and assessed for goodness of fit following Zuur et al. (2009). Generalized linear mixed models were used for analyzing count (arthropod catches and weed species richness) and proportion (marketable produce) data, following the same procedure but without pre-modelling data transformations. F-tests on the models were performed using Satterthwaite's method and the effect of predictor variables was considered significant at $p < 0.05$. Post-hoc tests on the treatment effect models were conducted to make pairwise comparisons between treatments using Tukey's HSD (0.95 confidence level). For model analyses we used the *lme4* package (Bates et al. 2015), and for post-hoc tests we used the *emmeans* package (Lenth 2019).

We used multi-variate analysis to disentangle the effect of increased diversity in each dimension on the performance of multiple AES indicators simultaneously. Principal components analysis (PCA) was used to give a low-dimensional overview of the data and show important sources of variation in the data. PCA was applied to each individual crop (potato, cabbage, and wheat; grass was not included in this analysis). In each instance only the indicator variables relevant to that crop were used in the PCA (see Table 5.1), and we did not include soil indicators. The data were first corrected for the effects of field and study year by applying a two-factor ANOVA model with field and year as main factors and then PCA were applied on the residuals of these models. Objects with too many missing values (more than half of all measurements) were removed, otherwise a few missing values were imputed with that variable's mean value so as not to influence the PCA results (Dray and Josse 2015). This can result in some cases in a whole treatment being excluded from the analysis. In the biplots resulting from the PCA, the three indicators comprising the temporal, spatial, and genetic diversity scores were projected into the biplots. In this analysis, we used the raw, un-scaled time, space, and genes diversity scores as the PCA method already involves scaling. We also calculated Pearson correlation coefficients between all variables (AES indicators and diversity scores) and the principal components. In analyzing these coefficients, we set a threshold of 0.3 for determining that a correlation was relevant.

5.3. Results

5.3.1. Effects of treatment on AES delivery

Here we unpack the results for each AES indicator on the basis of treatment. Overall, we found few strong signals indicating either an advantage or disadvantage of one treatment over another when compared to the references. For each AES indicator the effects of diversification practices varied, and effects varied further between crops.

We analyzed two soil fertility indicators, plant-available N and SOM content for the two crop pairs. PIXEL was not included in this analysis because it was only measured in one year. Interactions between year, crop pair, and treatment were tested during model selection and found to be not significant, so they were dropped from the soil models. The results showed no differences in N between treatments, although there was a significant effect of year ($p < 0.001$) with a general decline in available N from 2018 (22.6 kg ha^{-1} ± 0.64) to 2021 (15.7 kg ha^{-1} ± 0.79). We observed no difference in SOM between the start and finish of the experiment, however SOM contents were significantly lower in STRIP_DIV (3.24 % ± 0.10, $p < 0.001$) than the other treatments (see Appendix A5.5).

The results of the yield and crop quality are shown in Table 5.3 and Table 5.4. Neither cabbage nor potato yields were significantly different between the large-scale reference (REF_1) and the strip treatments. For wheat, both strip and pixel cropping produced lower yields than the monocultural reference. REF_1 yielded below organic standards for cabbage and wheat but within range for potatoes (KWIN-AGV 2018). For each crop there were some differences between strip treatments, with STRIP and STRIP_LEG yielding higher than STRIP_VAR for cabbage, and STRIP and STRIP_VAR yielding higher than STRIP_LEG for wheat. We found two instances of significantly better quality results in strips compared to the references: TKW (but only compared to small-scale REF_2, which did very poorly overall in terms of yield) and potato quality were both higher in STRIP_LEG than the monoculture reference. Within the strip treatments, wheat protein content was higher in STRIP_VAR compared to STRIP_LEG. All diversification treatments produced mean wheat grain protein contents above the common baking quality standard of 12% (NBC 2021), whereas the two references did not. The PIXEL treatment performed notably poorly on cabbage yield and quality, although the yield results were not significantly different than REF_1. Potato yield and quality were also notably and significantly lower in PIXEL compared to all other treatments. TKW was significantly lower in PIXEL compared to all strip treatments but not compared to the references.

Table 5.3. Effects of diversification treatments on fresh yields of cabbage, wheat, and potato at the Droevendaal experiment, 2018-2020. Means (± standard error) followed by the same letter in the same column are not significantly different (Tukey HSD, 0.95 confidence level).

	Fresh yield (kg m^{-2})		
Treatment	cabbage	wheat	potato
REF_1	1.76 (± 0.09) abc	0.35 (± 0.12) d	3.29 (± 0.10) b
REF_2	3.02 (± 0.23) c	0.07 (± 0.01) ab	2.32 (± 0.12) b
STRIP	2.66 (± 0.10) c	0.21 (± 0.02) c	3.04 (± (0.08) b
STRIP_VAR	2.11 (± 0.15) b	0.17 (± 0.02) bc	2.58 (± (0.09) b
STRIP_LEG	2.58 (± 0.11) c	0.12 (± 0.02) a	2.43 (± 0.09) b
STRIP_DIV	2.67 (± 0.28) bc	0.13 (± 0.03) abc	2.22 (± 0.11) b
PIXEL	1.17 (± 0.12) a	0.09 (± 0.04) abc	1.43 (± 0.07) a

Table 5.4. Effects of diversification treatments on crop quality indicators at the Droevendaal experiment, 2018-2020. Means (± standard error) followed by the same letter in the same column are not significantly different (Tukey HSD, 0.95 confidence level).

	Proportion marketable		Thousand kernel weight (g)	Grain protein content (%)
Treatment	cabbage	potato	wheat	
REF_1	0.77 (± 0.046) b	0.84 (± 0.011) b	38.9 (± 0.73) abc	9.06 ab
REF_2	----	0.76 (± 0.036) b	38.0 (± 0.56) ab	11.3 (± 0.24) ab
STRIP	0.82 (± 0.044) b	0.81 (± 0.019) b	38.3 (± 0.44) bc	13.0 (± 0.29) ab
STRIP_VAR	0.78 (± 0.057) b	0.77 (± 0.025) b	39.2 (± 0.81) bc	13.6 (± 0.39) b
STRIP_LEG	0.83 (± 0.043) b	0.82 (± 0.018) c	39.8 (± 0.59) c	12.6 (± 0.21) a
STRIP_DIV	0.85 (± 0.030) b	0.80 (± 0.029) bc	41.9 (± 0.78) bc	12.3 (± 0.35) ab
PIXEL	0.07 (± 0.041) a	0.57 a	37.6 (± 2.42) a	12.7 (± 0.40) ab

The data appeared to show a trend of decreasing weed cover when moving towards more diverse strip treatments. However, the only treatment with significantly reduced weed cover compared to the reference (6.88% ± 1.19) was STRIP_LEG (3.54% ± 0.48, $p < 0.001$), although STRIP_LEG also had lower weed species richness (4.64 ± 0.43) and Shannon diversity (0.98 ± 0.08) than the reference (7.54 ± 0.58 species richness, 1.45 ± 0.08 Shannon Index). PIXEL plots had significantly more cover by weeds than all other treatments (16.3% ± 2.14); this can be related directly to the selective hand-weeding approach used there.

5.3.2. Effects of system diversity on AES delivery

In this section we present the results of the linear modeling analyses done on the basis of diversity scores. Taking into account the large jump in management methods when moving from the strip treatments to PIXEL, we conducted the analyses twice: once with and once without the PIXEL treatment data included. The results are visualized in this way as well (Fig. 5.2, see also the data in table format in Appendix A5.7).

We observed several positive relationships between diversity score and performance indicators which were significant both with and without PIXEL data included in the analysis. These were: activity density of NEs ($p < 0.001$ with and without PIXEL), wheat protein content ($p < 0.001$ with and without PIXEL), and weed species Shannon diversity ($p < 0.001$ with and without PIXEL). In one instance we saw a positive effect of system diversity that no longer held when PIXEL was excluded: the observed increase in weed species richness as an effect of system diversity was only significant with PIXEL data ($p = 0.046$), and the effect was still positive but no longer significant without PIXEL data.

In another case we found that the diversity increase induced opposite effects when PIXEL was included vs. not. Without PIXEL, weed cover decreased significantly with increasing system diversity ($p = 0.013$) indicating an advantage in the more diverse strip treatments. When PIXEL data was included in the weed cover analysis, the results showed a substantial increase in weed cover with increasing system diversity ($p = 0.003$).

We also observed negative effects of increasing crop diversity on yield and quality for both cabbage and potato with PIXEL data included. However, when PIXEL data was excluded, these negative relationships were no longer significant. There was only one negative correlation with increasing diversity that was maintained with and without PIXEL, and that was for SOM content. For all other AES indicator and crop combinations there was no observable effect of increasing crop diversity. For some indicators, other factors were significant. Available N was again related to year ($p < 0.001$), and both crop pair ($p = 0.003$) and sample round ($p < 0.001$) had an effect on NE activity density, as well as the interaction between crop pair and sample round ($p = 0.002$).

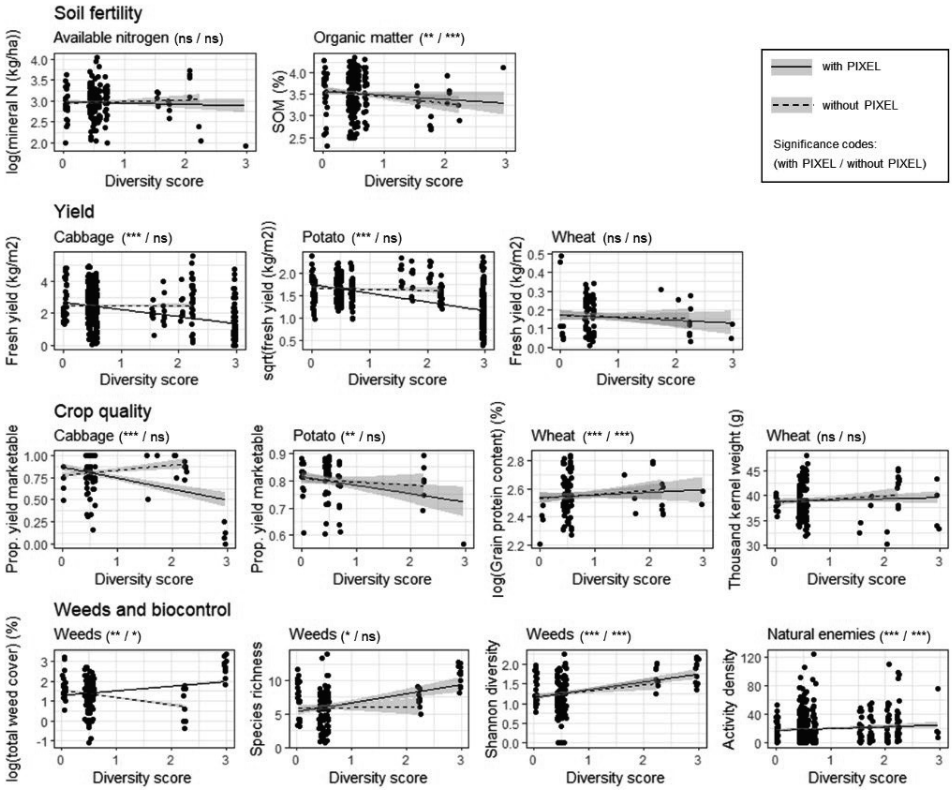


Figure 5.2. Response relationships between increasing structural crop diversity (diversity score, x axes) and system performance indicators (y axes) at the Droevendaal experiment from 2018-2020. Solid lines show the modelled response with PIXEL data included and dashed lines show the modelled response without PIXEL data included. Significance codes in parentheses next to indicator titles refer to the significance of the modelled response (with PIXEL / without PIXEL). Significance codes: *** $p < 0.001$; ** $p = 0.001$; * $p = 0.01$; ns = not significant.

5.3.3. Contribution of diversity dimensions to AES delivery

Fig. 5.3 shows the PCAs carried out per crop for production, weeds, and biocontrol potential indicators. The first two principal components (PCs) explain 76.8% of the variance for cabbage, 58.5% for wheat, and 60.8% for potato. In the cabbage ordination plot (Fig. 5.3a) it is clear that the space, time, and genes score are each correlated negatively with PC1 (Table 5.5), in opposition to the measured production indicators. The most diverse treatment (PIXEL) is located in the bottom left quadrant of the plot, opposite the production variables. The angle between NE catches and production indicators is orthogonal, as well as between NE catches and the diversity score indicators, indicating no observable relationship. For wheat (Fig. 5.3b), fresh yield is strongly correlated with the two weed species diversity indicators (Table 5.5), all three of which are in opposition to thousand kernel weight. Again, the angle between NE catches and fresh yield is orthogonal. Neither the time nor genes scores were correlated with either PC, and the space score did not vary between the plotted treatments. In the potato ordination plot (Fig. 5.3c), a positive relationship between NE catches and crop quality is observable along PC1. Space scores again did not vary between the plotted treatments, but the time and genes scores were both positively correlated with PC1, which was characterized by higher NE catches and marketable yield proportion. The time and genes scores were orthogonal to fresh yield, which characterized PC2.

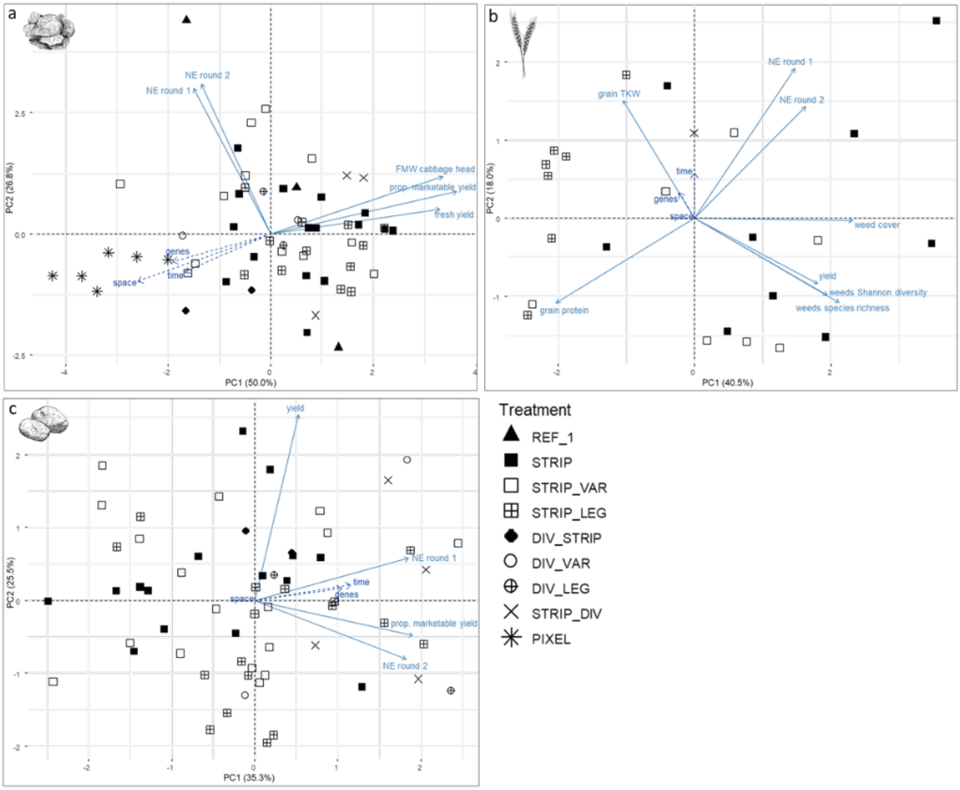


Figure 5.3. Ordination plots for principal component analyses of production, weed control and biocontrol potential indicators per crop. Treatments were dropped from the analysis if too many values were missing from the dataset.

Table 5.5. Correlation coefficients of variables and projected factors in the PCAs for production, weed, and biocontrol potential indicators per crop. For explanatory factors (space, time, and genes scores), we set a threshold of 0.3 to determine a correlation as relevant; these instances are indicated in bold.

	Cabbage		Wheat		Potato	
	PC1	PC2	PC1	PC2	PC1	PC2
Fresh yield	0.8315	0.1282	0.6268	-0.2908	0.1905	0.9265
Fresh marketable weight cabbage head	0.8443	0.2982				
Proportion of yield that is marketable	0.9116	0.2186			0.6927	-0.1776
Grain thousand kernel weight			-0.3625	0.5237		
Grain protein content			-0.7043	-0.3751		
Total cover by weeds			0.8033	-0.0104		
Shannon diversity of weed species			0.6736	-0.3407		
Weeds species richness			0.7343	-0.3738		
Natural enemies round 1 (June/July)	-0.3816	0.7593	0.5110	0.6648	0.6747	0.2096
Natural enemies round 2 (Aug./Sept.)	-0.3429	0.7814	0.5660	0.4956	0.6625	-0.2942
Time score	**-0.4317**	-0.1993	-0.0009	0.1891	**0.4182**	0.0767
Space score	**-0.6575**	-0.2470	0.0000	0.0000	0.0000	0.0000
Genes score	**-0.4832**	-0.1447	-0.0820	0.1196	**0.3846**	0.0592

5.4. Discussion

5.4.1. Prospects for strip and pixel cropping

By conducting our data analysis on the basis of experimental treatment, we sought to link specific diversification practices to the performance of different AES indicators within the context of a Dutch field experiment. The main aim of this analysis was to gain further insight into what might be the resolution of diversity—translated as actual field practices—at which AES delivery was greatest within this particular context. The analysis showed, however, that such a conclusion is not so easily generalizable, as the results varied between AES indicators and between crops.

We saw only a few strong signals of particular practices performing better than others, and these results were not consistent: no single treatment performed better than the rest across AES indicators. Rather, we observed crop-related trends and effects related to temporal dynamics. The variation in mineral N levels we observed between years likely had to do with environmental factors and timing of cultivation practices from year to year; N levels are known to fluctuate substantially through growing seasons and between seasons (van der Burgt et al. 2006). NE activity density was also related to the effect of sampling time, and these differences likely had to do with the arthropods' responses to weather and resource conditions.

The broad lack of observable treatment effects could be explained with various theories related to the temporal—spatial scale of the experiment (see Section 4.4.) or to the resolution of the data. For example, for NEs we looked only at abundance and not at community composition at the species level. In doing so we could have missed potential treatment effects, as it has been shown for instance that certain ground beetle species prefer particular crops and crop arrangements over others (Allema et al. 2015; Allema et al. 2019). With both NEs and weeds, species richness is of interest from the perspective of biodiversity preservation, but species composition also matters in regard to AES delivery when the presence of certain species or functional groups may be more predictive of associated effects (Bàrberi et al. 2018; Dainese et al. 2019; Dassou and Tixier 2016). A lack of treatment effect can in some cases be seen as a positive outcome. For instance, it is notable the treatments which did not receive animal manure (STRIP_LEG and STRIP_DIV) showed no significant differences in available N compared to those that did.

When we moved next into an analysis on the basis of diversity score, generalizable trends became clearer, providing some insights into how far down the heterogeneity continuum the benefits of system diversity might extend and under what management conditions. Overall, we observed that positive effects of increasing diversity were robust, while the majority of observed significant negative effects of diversity score on the measured indicators only held when PIXEL data was included in the analysis. The only exception to this trend was SOM content, although given the time scale at which soil composition changes generally occur, it is not likely that the observed differences would be the result of cultivation practices after just three growing seasons (Powlson and Neal 2021).

Taking the results of the treatment-based and diversity score-based analyses together, the findings suggest on one hand that the ecological benefits (as measured by associated biodiversity and biocontrol potential indicators) of crop diversification continue as far down the heterogeneity spectrum as our experiment extended, which is in line with ecological theory particularly for biodiversity-mediated services (Dassou and Tixier 2016; Fahrig et al. 2015; Rusch et al. 2013; Sirami et al. 2019). On the other hand, agronomic impacts (as measured by crop yield and quality) were either neutral, variable, or reached a limit at a resolution of heterogeneity equated with the most diverse strip cropping system, countering the agronomic theory (Li et al. 2009; van Oort et al. 2020; Yu et al. 2015). Jumping from diverse strips to the PIXEL system caused reductions in several production indicators, and in this jump we hypothesize that management became the limiting factor.

5.4.2. A management tipping point

The field experiment was designed to test a spectrum of structural in-field diversity on a conceptual scale with reference monocultures on one end and pixel cropping on the other, with various strip cropping treatments in between. In practice, however, the steps from treatment to treatment on this scale were not equally incremental: moving from the most diverse strip treatment (STRIP_DIV) to PIXEL is a much bigger step than moving from a less diverse strip to a more diverse strip. This is largely due to the management demands of a pixel plot versus a strip cropping plot, indicating what could be thought of as a management tipping point. We saw this point of inflection in the production indicator responses to diversity scores when moving from strips to pixels, suggesting that management is currently a limiting factor in achieving the full potential of diversity at resolutions higher than strip cropping.

Strip cropping can, for the most part, be done with common agricultural machinery and in our experiment the strips were managed in the same manner as in the monoculture references. This means that the same machines were used to do the same cultivation tasks at around the same time. Practices which require very targeted applications of inputs (e.g. pesticides, fertilizers) can be difficult in strip cropping layouts, particularly in narrower strips, but this is only really a problem in production systems that use agrochemicals. Other system design challenges such as field layout and crop rotations are being addressed in new design tools developed specifically for strip cropping systems (Juventia et al. 2022) and progress in this arena is moving quickly as more farmers take up the practice and learn from each other's experiences. Dutch farmers report anecdotally that strip cropping requires a different way of thinking about crop cultivation than monocultures, but that they like the challenge. Strip cropping thus seems to offer a viable scenario in the Dutch context in which agrobiodiversity can be enhanced while maintaining expected production measures and also potentially gaining in ecological performance, without tipping into an entirely new management regime.

Pixel cropping, other the other hand, hints at the ecological potential of moving beyond the management tipping point, but production standards appear to only be achievable with the development of new cultivation approaches and tools. In the pixel plots, we also aimed to duplicate as much as possible the management practices used in the rest of the experiment, however all tasks were done by hand rather than by machine and this imposed differences. Weeding is a key example of this. Increases in system diversity showed a reduction effect on weed cover up until PIXEL, echoing the findings of a recent meta-analysis which analyzed the effects of other forms of intercropping on weed suppression (Gu et al. 2021). The hand-weeding approach taken in the pixel plots likely inherently negated such an effect, and more weed cover could be expected. Agronomic measures of success such as yields and crop quality were also not significantly affected by diversity resolution until PIXEL was included in the analysis. Here the shortcomings of having different field workers managing crops individually and by hand and walking frequently through the plots could certainly have had impacts on the productivity and quality of the crops.

The key factors contributing to management challenges in pixel plots are scale (very small management units) and spatial configuration (a different crop every 50 cm). Both scale and spatial configuration have implications for crop—crop interactions and for mechanization potential. In pixel-sized units (in current experiments it has ranged from 0.25 m^2 – 2.25 m^2) with four different possible neighbors, the edge density in a pixel is very high. This is known to lead to greater delivery of AES at the landscape scale (Martin et al. 2019), but can also lead to greater competition—and generally more complex interactions—at the plant scale both above and below ground (Cappelli et al. 2022; Stomph et al. 2020; Weisser et al. 2017). It will be essential to learn more about what crops make good neighbors (Carrillo-Reche et al. submitted), and at what community sizes, when designing future pixel cropping systems—or any complex polyculture—for production aims. Plant breeding can also play a role in this regard, as to date breeding programs have focused primarily on traits relevant for monocultural growth environments (Bourke et al. 2021).

One way to reconcile the current management tipping point presented by pixel cropping is to consider each pixel a discrete farm field which will require cultivation tasks the same way a strip or a larger field would. The challenge then is to develop tools which can cultivate such small 'fields' arranged in broad assemblages. Farmers seeking to diversify their cropping systems in less complex ways (e.g. incorporating cereal—legume mixtures) already face implementation barriers related to technology (Meynard et al. 2018; Morel et al. 2020). The tools required to cultivate polycultures at large scales are far more technically challenging to design and develop (Sukkel 2020). Automation and robotics are often advertised as a solution to achieve more precise and efficient crop management (Duckett et al. 2018), and there is potential for these tools to be effective in a pixel cropping-type set-up, however to date the majority of the tools being developed are designed to operate only in monocultural conditions (Ditzler and Driessen 2022). The true potential of automation for amplifying complex cropping systems has yet to be seen, and does not come without heavy socio-political implications (Montenegro de Wit 2021; Sparrow and Howard 2020; Rose et al. 2021; Rotz et al. 2019).

5.4.3. Beyond space—time—genes?

The key aim of the multivariate analysis was to better understand the influence of each diversity dimension (time, space, genes) in achieving desirable agroecological outcomes and thereby facilitate further extension of the three-dimensional diversity heuristic as a predictive tool. Disentangling the effects of each dimension on the measured performance indicators would provide input for refining the diversity scoring system, allowing the weights of each dimension to be qualified in relation to AES delivery. However, our analysis revealed few concrete insights into the relative weight of each dimension within the context and scope of the experimental set-up. The effects of diversity dimensions that we did see appeared to vary between crops.

The clearest associations were provided by the cabbage analysis. Higher diversity scores in all three dimensions were in opposition to higher production indicator performance, with space having the strongest association. For cabbage, we could hypothesize thus that higher resolution diversity is not optimal from a production perspective, and that in particular spatial diversity is not advised unless levers for optimizing spatially diverse layouts—for example more competitive genotypes—are developed.

In potato, the time and genes scores were positively associated with higher NE catches and marketable yield proportion. Possible explanations for this association could be related to NE habitat availability, which would vary more frequently at higher temporal dimension scores. Better potato quality could in turn be related to higher NE catches which may indicate a stronger biocontrol effect on the main potato pest the Colorado beetle (*Leptinotarsa decemlineata*), however the experiment was not designed to assess this relationship. We could conclude that for potato, higher resolution temporal and genetic diversity can be beneficial for biocontrol potential and crop quality, however the effects may not translate to yield increases.

The wheat PCA showed no correlations between diversity dimensions and AES indicators, but fresh yield was strongly positively correlated with the two weed species diversity indicators. This result counters conventional knowledge on the relationship between weeds and crop yields, although it may indicate the benefit of more diverse weed communities (Hofmeijer et al. 2021). Further analysis into the taxonomic and functional composition of the weed community would be needed to further untangle this effect (Gaba et al. 2017).

Despite the lack of strong signals as to the effects of each dimension, the analysis conducted on the basis of compound diversity scores did show some clear trends, suggesting that the cumulative effect of diversifying—no matter which dimension(s) it came from—was more relevant in this context (organic arable farming in The Netherlands) than the effects of individual dimensions. For Dutch farmers, that could imply that diversifying in any dimension can be beneficial for enhancing AES delivery in general, although the use of dimension-specific practices with already well known AES associations (e.g. crop rotation and soil-borne disease control, Leoni et al. (2015)) remains relevant for achieving particular aims. Further studies investigating emergent properties in complex agroecosystems (e.g. Khumairoh et al. 2021) are needed in order to explore whether qualifying crop diversification practices on the basis of the time—space—genes dimensions would still be relevant or whether compound scores better capture the emergent effects. Such studies would facilitate discussions at national and regional levels around how policy should support farmers in implementing diversification practices (Antier et al. 2021).

5.4.4. Limitations of time and space

Several limitations of both the experimental approach and the diversity scoring system used in the analysis should be considered when interpreting the results presented here. These are related primarily to issues of temporal and spatial scale. Changes in soil fertility parameters are unlikely to be visible in just three cropping seasons (Bünemann et al. 2018; Powlson and Neal 2021), and this should be factored in especially when interpreting the SOM results. Similarly, the spatial scale of the experiment imposes certain limitations when seeking to make links between cropping practices and arthropod-mediated services. It is well known that different species operate at different spatial ranges, and that landscape-level factors can have a stronger influence on arthropod populations than field-level factors (Bakker et al. 2021; Thies and Tscharntke 1999). Further, the interplay between field- and landscape-scale dynamics is complex, highly context-dependent, and not well understood (Karp et al. 2018; van der Werf and Bianchi 2022). In addition to longer-term and larger-scale experiments, getting the most out of crop diversification will likely require coordination at community or regional scales (Geertsema et al. 2016; Steingröver et al. 2010).

In developing the method for quantifying cropping system structural diversity, we made assumptions about both temporal and spatial scales which may have an influence on the outcome of the method. Namely, we imposed a radius of 9 meters to describe the cropping system neighborhood. We made this choice within the context of the particular composition and scale of the field experiment we were working with, but a different radius could impact how cropping systems are scored in all three dimensions and thereby result in different outcomes (Botzas-Coluni et al. 2021; Steffan-Dewenter et al. 2002). In order to generalize the scoring method, a standardized approach to devising the neighborhood radius should be developed, subjected to sensitivity analysis, and tested. The composition of the indicators used to score each dimension may also be refined by taking into account local system properties, or by adopting system complexity measures from disciplines beyond agriculture and landscape ecology (e.g. Paoli et al. 2016).

5.5. Conclusions

In this study we paired empirical data with a novel assessment framework to assess the potential of high-resolution diversified cropping systems to meet production and ecological aims in the context of an organic farming experiment in The Netherlands. We can conclude from this study that ecological aims can be achieved through increasing resolutions of crop diversity without detracting from production aims, up to a point (in this study, somewhere between STRIP and STRIP_DIV, depending on the crop). After that point, we cannot yet draw conclusions about what is possible because current technological limitations put a ceiling on what can be achieved in industrialized contexts. Further, we conclude that understanding the potential of crop diversification at high resolutions is probably not only about unravelling the individual influences of temporal, spatial, and genetic effects. Accounting for interacting and cumulative effects between dimensions will likely be more relevant for further extending the three-dimensional diversity framework towards predictive applications, and for developing appropriate tools for smoothing out the management tipping point. To do this, more work is needed in a greater diversity of cropping systems and environmental contexts, and at longer temporal and wider spatial scales.

Acknowledgements

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Appendix 5

A5.1. Weather data

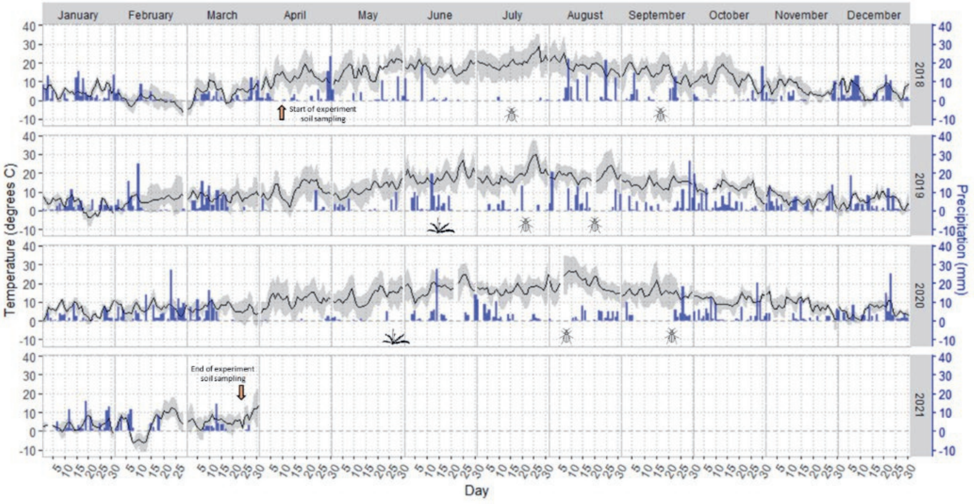

Figure A5.1.1. Weather at the Droevendaal experiment site in Wageningen, NL during the study, from 2018 until final soil sampling in March 2021. Black line shows mean temperature (degrees Celsius), grey ribbons span daily minimum and maximum temperatures (degrees Celsius), and blue bars are the sum daily precipitation (mm). Arrows indicate dates of soil sampling, beetle icons indicate dates of pitfall trapping events, and plant icons indicate dates of weed surveys. The hot summer in 2018 and dry spring in 2020 were considered locally as weather anomalies. Temperature and precipitation data obtained from the weather station De Veenkampen operated by Wageningen University.

A5.2. Field experiment layout

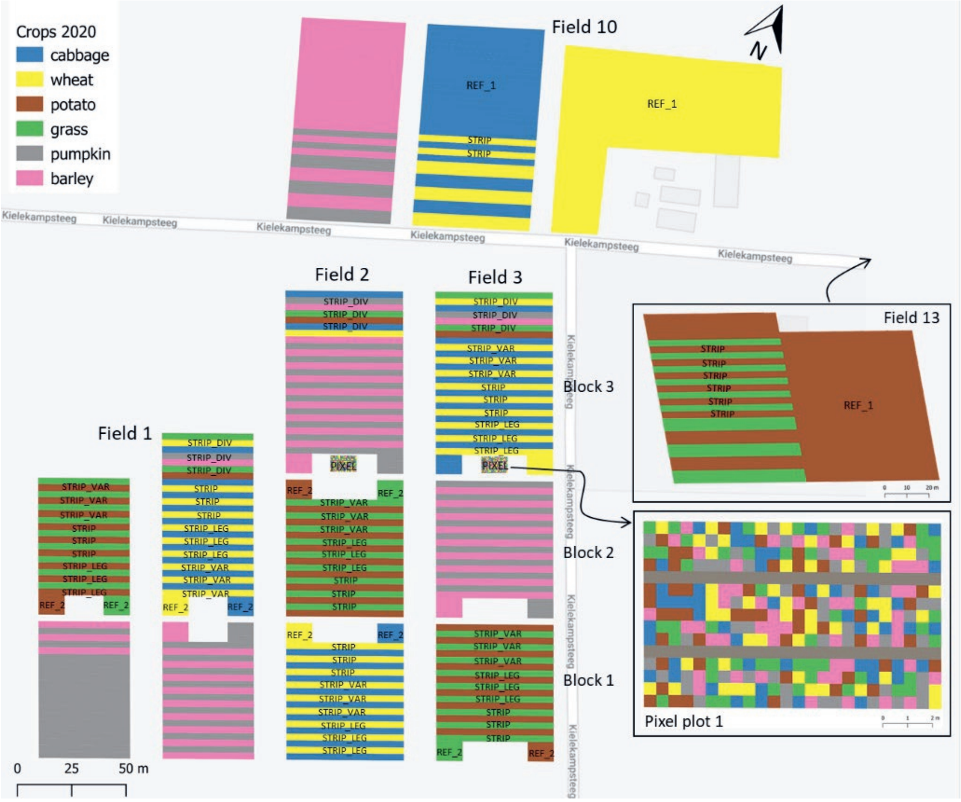

Figure A5.2.1. Layout of the experimental fields at the Droevendaal Experimental and Training Farm in Wageningen, NL. Map shown is for the 2020 growing season. Configurations of Fields 1-3 remained the same for all experiment years; large-scale reference fields moved from year to year but always included a connected strip block in the same field. Pixel plot 2 layout not shown.

A5.3. Crop management

Table A5.3.1. Crop management information for the treatments sown at the Droevendaal experiment, 2018-2020.

Main crop (all treatments)	Main crop variety (all treatments)	Added variety(s) (STRIP_VAR, DIV_VAR, STRIP_DIV, PIXEL)	Added legume (STRIP_LEG, DIV_LEG, STRIP_DIV, PIXEL)
Cabbage	Rivera	Christmas Drumhead	
Wheat	2018: Spring wheat (Lennox) 2019-2020: Winter wheat (Kelvin)	2018: Spring wheat (Lavette) 2019-2020: Winter wheat (Julius)	2018: Spring faba (Pyramid) 2019: Winter faba (Tundra) 2020: Winter faba (Lemken)
Potato	Agria	Carolus, Alouette	
Grass	2018: Italian rye (Melbolt) 2019-2020: Italian rye (Danergo)	2018: English rye (Sputnik, Humbi 1) + tall fescue 2019: English rye (Maurice) + Timothy 2020: Perennial rye	Red clover (Salino)

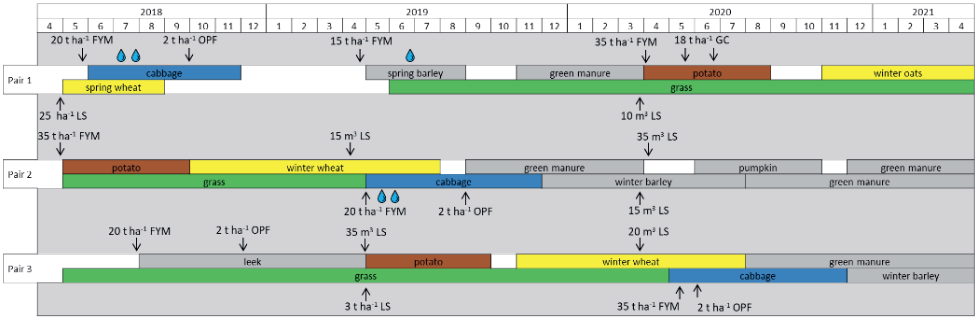

Figure A5.3.1. Crop rotation and timing of fertilization and irrigation for the three crop pairs at the Droevendaal experiment during the study period. FYM = farmyard manure (solid cattle manure), LS = liquid cattle manure (slurry), OPF = organic plant-based fertilizer, GC = grass—clover mulch. Treatments including a legume in the rotation (STRIP_LEG, DIV_LEG, STRIP_DIV, PIXEL) did not receive any animal manure fertilizer. These treatments received OPF and were mulched with grass-clover at a rate of 18 t ha-1, once per year in all crops except potato which was mulched twice in 2020.

A5.4. Diversity scores for experiment treatments

Table A5.4.1. Diversity scores (individual dimensions and compound diversity score) calculated for each crop—treatment combination employed in the cropping system experiment.

Crop	Treatment	Time score	Space score	Genes score	Diversity score
Cabbage	REF_1	0.000	0.000	0.000	0.000
	REF_2	0.000	0.041	0.000	0.041
	STRIP	0.143	0.236	0.063	0.442
	STRIP_VAR	0.143	0.236	0.188	0.567
	STRIP_LEG	0.143	0.236	0.125	0.504
	DIV_STRIP	1.000	0.236	0.313	1.549
	DIV_VAR	1.000	0.236	0.813	2.049
	DIV_LEG	1.000	0.236	0.500	1.736
	STRIP_DIV	1.000	0.236	1.000	2.236
	PIXEL	0.964	1.000	1.000	2.964
Wheat	REF_1	0.000	0.000	0.000	0.000
	REF_2	0.000	0.041	0.000	0.041
	STRIP	0.143	0.236	0.063	0.442
	STRIP_VAR	0.143	0.236	0.188	0.567
	STRIP_LEG	0.143	0.236	0.125	0.504
	DIV_STRIP	1.000	0.236	0.313	1.549
	DIV_VAR	1.000	0.236	0.813	2.049
	DIV_LEG	1.000	0.236	0.500	1.736
	STRIP_DIV	1.000	0.236	1.000	2.236
	PIXEL	0.964	1.000	1.000	2.964
Potato	REF_1	0.000	0.000	0.000	0.000
	REF_2	0.000	0.041	0.000	0.041
	STRIP	0.143	0.236	0.063	0.442
	STRIP_VAR	0.143	0.236	0.313	0.692
	STRIP_LEG	0.143	0.236	0.125	0.504
	DIV_STRIP	1.000	0.236	0.313	1.549
	DIV_VAR	1.000	0.236	0.813	2.049
	DIV_LEG	1.000	0.236	0.500	1.736
	STRIP_DIV	1.000	0.236	1.000	2.236
	PIXEL	0.964	1.000	1.000	2.964
Grass	REF_1	0.000	0.000	0.000	0.000
	REF_2	0.000	0.041	0.000	0.041

STRIP	0.143	0.236	0.063	0.442
STRIP_VAR	0.143	0.236	0.313	0.692
STRIP_LEG	0.143	0.236	0.125	0.504
DIV_STRIP	1.000	0.236	0.313	1.549
DIV_VAR	1.000	0.236	0.813	2.049
DIV_LEG	1.000	0.236	0.500	1.736
STRIP_DIV	1.000	0.236	1.000	2.236
PIXEL	0.964	1.000	0.938	2.902

A5.5. Soil fertility parameters by treatment

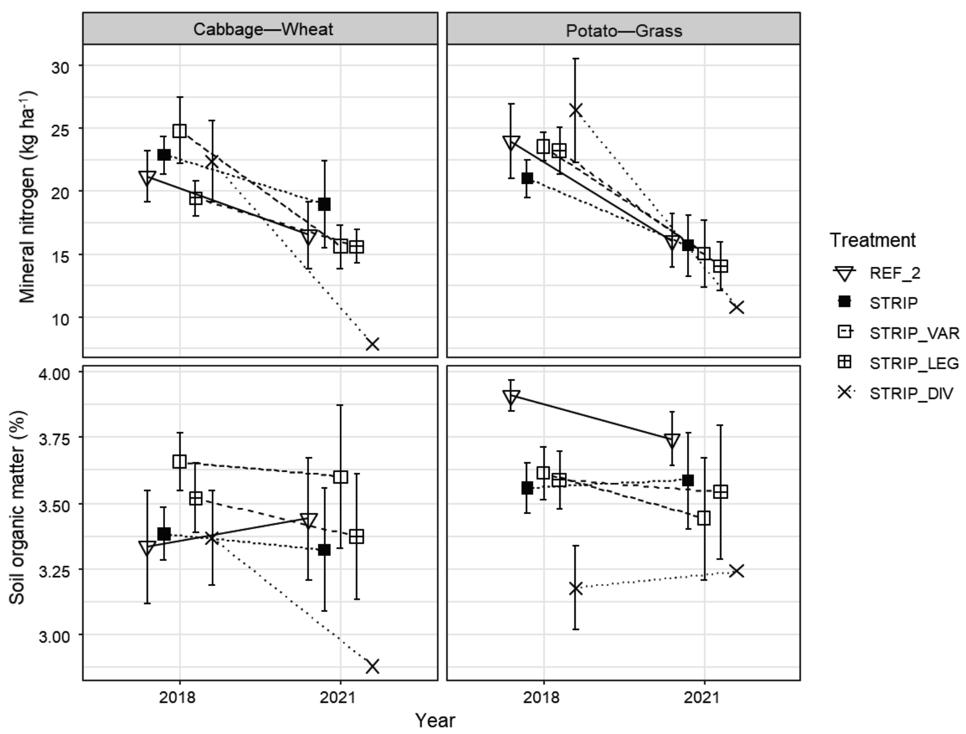

Figure A5.5.1. Soil fertility indicator measurements per treatment at the start (2018) and finish (2021) of the experiment.

A5.6. Weed and biocontrol potential results by treatment

Table A5.6.1. Effects of diversification treatments on weed cover and diversity indicators in wheat at the Droevendaal experiment, 2018-2020. Means (± standard error) followed by the same letter in the same column are not significantly different (Tukey HSD, 0.95 confidence level).

Treatment	Weed cover (%)	Weed species richness	Weed species Shannon diversity index
REF_1	NA	NA	NA
REF_2	6.88 (± 1.19) b	7.54 (± 0.584) b	1.45 (± 0.080) b
STRIP	6.06 (± 0.67) b	5.36 (± 0.440) ab	1.18 (± 0.075) ab
STRIP_VAR	4.65 (± 0.46) ab	6.28 (± 0.579) ab	1.32 (± 0.097) b
STRIP_LEG	3.54 (± 0.48) a	4.64 (± 0.428) a	0.98 (± 0.080) a
STRIP_DIV	3.08 (± 0.67) ab	7.22 (± 0.434) ab	1.68 (± 0.089) b
PIXEL	16.3 (± 2.14) c	10.8 (± 0.501) b	1.80 (± 0.091) b

Table A5.6.2. Effects of diversification treatments on activity density of epigeic arthropod natural enemies (NEs) at the Droevendaal experiment, 2018-2020. Means (± standard error) followed by the same letter in the same column are not significantly different (Tukey HSD, 0.95 confidence level).

		NE activity density (total catch)
Treatment		
	REF_1	19.2 (± 1.64) ab
	REF_2	NA
	STRIP	18.0 (± 1.45) a
	STRIP_VAR	17.5 (± 1.60) a
	STRIP_LEG	16.2 (± 1.48) a
	STRIP_DIV	24.0 (± 4.12) b
	PIXEL	23.8 (± 6.20) ab
Sample round		
	1	28.2 (± 1.15) b
	2	7.79 (± 0.52) a
Crop pair		
	cabbage--wheat	16.8 (± 0.95) a
	potato--grass	19.3 (± 1.20) a
Crop pair * sample round		
	cabbage--wheat catch 1	24.9 (± 1.40) b
	cabbage--wheat catch 2	8.77 (± 0.73) a
	potato--grass catch 1	30.8 (± 1.72) c
	potato--grass catch 2	6.96 (± 0.72) a

A5.7. Diversity score analysis results

Table A5.7.1. Results of mixed linear modelling analyses for each cropping system performance indicator, conducted once with PIXEL treatment data included and once with PIXEL treatment data excluded. Numbers in bold have been transformed (log or square root) during modelling and have not been back-transformed.

				Results *with* PIXEL included					Results *without* PIXEL included			
Indicator	Crop	Unit		Estimate	Std. error	*p* value			Estimate	Std. error	*p* value	
Soil fertility	all crops	Available N (kg/ha2)	(Intercept)	**3.14077**	**0.09539**	0.0954		(Intercept)	**3.11297**	**0.08993**	0.0000	
			Diversity score	**-0.06718**	**0.05636**	0.0564	ns	Diversity score	**-0.02297**	**0.05893**	0.6980	ns
			year2021	**-0.42605**	**0.05075**	0.0508	***	year2021	**-0.40921**	**0.05089**	0.0000	***
	all crops	SOM (%)	(Intercept)	3.6748	0.21212	0.0010		(Intercept)	3.72013	0.20053	0.0007	
			Diversity score	-0.23651	0.07397	0.0017	**	Diversity score	-0.32145	0.07634	0.0000	***
			year2021	-0.01428	0.05711	0.8029	ns	year2021	-0.0391	0.05614	0.4871	ns
Yield	potato	Fresh yield (kg/m2)	(Intercept)	**1.76082**	**0.115**	0.0035		(Intercept)	**1.75709**	**0.10939**	0.0000	
			Diversity score	**-0.21297**	**0.01144**	<2e-16	***	Diversity score	**-0.00947**	**0.01744**	0.5880	ns
	wheat	Fresh yield (kg/m2)	(Intercept)	**9.4286**	**2.9348**	0.0013		(Intercept)	9.27474	3.1276	0.0030	
			Diversity score	**-0.2725**	**0.5692**	0.6322	ns	Diversity score	-0.05309	0.63706	0.9336	ns
	cabbage	Fresh yield (kg/m2)	(Intercept)	2.65239	0.22398	0.0001		(Intercept)	2.45636	0.18849	0.0000	
			Diversity score	-0.41049	0.05732	0.0000	***	Diversity score	-0.10893	0.09727	0.2640	ns

Crop quality	wheat	Grain protein content (%)	(Intercept)	**2.46963**	**0.10086**	0.0112		(Intercept)	**2.44231**	**0.05297**	0.0000	
			Diversity score	**0.07087**	**0.01662**	0.0000	***	Diversity score	**0.11702**	**0.02091**	0.0000	***
	wheat	Thousand kernel weight (g)	(Intercept)	38.7278	1.623	0.0010		(Intercept)	38.746765	2.114972	0.0010	
			Diversity score	0.1488	0.3692	0.6876	ns	Diversity score	-0.007824	0.373053	0.9833	ns
	potato	Proportion marketable	(Intercept)	**1.51611**	**0.18559**	0.0000		(Intercept)	1.42341	0.1361	<2e-16	
			Diversity score	**-0.08034**	**0.02902**	0.0056	**	Diversity score	0.03447	0.03637	0.3430	ns
	cabbage	Proportion marketable	(Intercept)	**2.6123**	**0.5885**	0.0000		(Intercept)	1.4734	0.4848	0.0024	
			Diversity score	**-0.8235**	**0.126**	0.0000	***	Diversity score	0.2162	0.1604	0.1776	ns
Weeds	wheat	Total cover by weeds (%)	(Intercept)	**1.29445**	**0.1899**	0.0271		(Intercept)	**1.5595**	**0.1959**	0.0231	
			Diversity score	**0.2656**	**0.08648**	0.0026	**	Diversity score	**-0.3297**	**0.1313**	0.0133	*
	wheat	Shannon diversity index	(Intercept)	1.07385	0.13453	0.0003		(Intercept)	1.07383	0.14124	0.0003	
			Diversity score	0.25119	0.04378	0.0000	***	Diversity score	0.24884	0.07247	0.0008	***

	wheat	Weed species richness	(Intercept)	**1.53732**	**0.35127**	0.0000			(Intercept)	1.57343	0.18256	<2e-16	
			Diversity score	**0.07265**	**0.03641**	0.0460	*		Diversity score	0.13039	0.07417	0.0788	ns
Biocontrol potential	all crops	Activity density (total catch)	(Intercept)	**3.0001**	**0.22047**	< 2e-16			(Intercept)	2.99472	0.22163	< 2e-16	
			Diversity score	**0.22166**	**0.05856**	0.0002	***		Diversity score	0.23739	0.0623	0.0001	***
			crop_pair potato-grass	**0.26202**	**0.08909**	0.0033	**		crop_pair potato-grass	0.25658	0.08979	0.0043	**
			Sample round catch_2	**-1.21675**	**0.08841**	< 2e-16	***		Sample round catch_2	-1.21456	0.0892	< 2e-16	***
			crop_pair potato-grass:sample round catch_2	**-0.37318**	**0.12088**	0.0020	**		crop_pair potato-grass:sample round catch_2	-0.37645	0.12145	0.0019	**

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Chapter 6

Automating agroecology: how to design a farming robot without a monocultural mindset?

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Abstract

Robots are widely expected—and pushed—to transform open-field agriculture, but these visions remain wedded to optimizing monocultural farming systems. Meanwhile there is little pull for automation from ecology-based, diversified farming realms. Noting this gap, we here explore the potential for robots to foster an agroecological approach to crop production. The research was situated in The Netherlands within the case of *pixel cropping*, a nascent farming method in which multiple food and service crops are planted together in diverse assemblages employing agroecological practices such as intercropping and biological pest control. Around this case we engaged with a variety of specialists in discussion groups, workshops, and design challenges to explore the potential of field robots to meet the multifaceted demands of highly diverse agroecological cropping systems. This generated a spectrum of imaginations for how automated tools might—or might not—be appropriately used, ranging from fully automated visions, to collaborative scenarios, to fully analogue prototypes. We found that automating agroecological cropping systems requires finding ways to imbue the ethos of agroecology into designed tools, thereby seeking to overcome tensions between production aims and other forms of social and ecological care. We conclude that a rethinking of automation is necessary for agroecological contexts: not as a blueprint for replacing humans, but making room for analogue and hybrid forms of agricultural work. These findings highlight a need for design processes which include a diversity of actors, involve iterative design cycles, and incorporate feedback between designers, practitioners, tools, and cropping systems.

Keywords: open-field agriculture; mechanization; pixel cropping; crop diversification; co-bot

6.1. Introduction

A drive towards automation of both physical and cognitive work processes fuels increasingly ubiquitous applications of robots2F[1], for example in manufacturing, mobility, entertainment, health care, security, and food processing. In open-field farming3F[2] too, robotization is being presented as inevitable (Blackmore et al. 2005; Harris 2018). Commercial entities and research institutions are funneling tremendous resources into the development, testing, and production of robotic equipment for open-field settings, although these tools remain largely in research and development environments and have yet to gain traction among farmers the way applications in other agricultural realms have, such as automated milking systems (Bechar and Vigneault 2016; Duckett et al. 2018). Nonetheless, in the wake of the COVID-19 pandemic it has been projected that investments into automated open-field farming technology will only accelerate (van der Boon 2020).

Reading popular media coverage of advances in open-field agricultural automation gives a particular view of the way crop husbandry is being conceived, revealing the dominant monocultural approach—cultivating a sole crop in a given area—underpinning these developments. Recent headlines like those in *The Guardian* announce a particular direction for automation: "The rise of the robot farmer: We'll have space bots with lasers, killing plants" (Harris 2018); or the latest, "Killer farm robot dispatches weeds with electric bolts" (Carrington 2021). The dualisms evident in these titles (crop/weed, nature/(agri)culture) assume a particular approach to farming that is both precipitated and perpetuated by narrowly delimited measures of success.

The dominant narratives promoting robots in open-field agriculture anticipate that they will optimize the efficiency of agricultural tasks and inputs, thereby decreasing the need for human labor and the environmental impacts of monocultural, industrial agriculture in mechanized contexts (Bechar and Vigneault 2016; Duncan et al. 2021). The potential for robots to increase the sustainability of industrial-scale cropping serves as a loud selling point (Duckett et al. 2018), as it is widely acknowledged that industrial monocultures contribute heavily to global environmental degradation and that alternatives are urgently needed (Campbell et al. 2017). Yet the expected gains in sustainability afforded by robotization are most often credited to the increase in precision with which they will apply agrochemicals or contain soil damage, and not to their capacity to facilitate agricultural practices that do not rely on environmentally problematic methods in the first place (Kuch et al. 2020; Miles 2019).

Crop diversification has long been employed in farming systems as way to enhance ecological controls and spread risk and is gaining increasing attention in research and policy agendas as

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[1] We tentatively define *robot*s as "perceptive programmable machines", following Bechar and Vigneault (2017).

[2] We use the term 'open-field farming' to refer to cropping systems in which plants (arable and vegetable crops) are grown outdoors in soil, as opposed to in controlled growth environments such as greenhouses.

scientific findings point to its potential to mitigate the negative ecological impacts of monocultural production (Beillouin et al. 2021; Tamburini et al. 2020). Agroecological farming systems, which are grounded in ecological processes and knowledge and utilize various forms of crop diversification as a foundational practice (Francis et al. 2003), have been shown to provide agronomically, ecologically, and socially viable alternatives to the industrial monoculture model (Boeraeve et al. 2020; Juventia et al. 2021; van der Ploeg et al. 2019). Despite the fact that some form of mechanization (and possibly automation) will be necessary if diversified and agroecological approaches are to be translated and amplified in the industrialized contexts where they are most needed, technology makers have not yet focused intently on automation in such systems.

Following a well-documented trajectory of innovation in agriculture throughout which machines and farming systems have co-evolved (Magrini et al. 2019; Sassenrath et al. 2008), the majority of robots being developed for open-field arable and vegetable contexts are designed to function in monocultures and to fortify mutually reinforcing concerns of these systems: reducing labor inputs, increasing efficiency, and perfecting the uniformity of crop stands (Fountas et al. 2020). Key features of robots that could make them uniquely suited for applications in diversified settings—their potential to be light weight, modular or multifunctional, highly mobile, autonomous, and teachable—are not used to embrace heterogeneity, but are more often called in to further homogenize already monocultural production environments (Grieve et al. 2019). In addition to a lack of suitable tools being developed, there appears to be little pull from the agroecological, diversified farming realm to design automated farming machinery (Bellon Maurel and Huyghe 2017), even though farmers who are interested in diversifying their cropping systems have cited a lack of appropriate tools as a substantial barrier (Morel et al. 2020). The question of what automation and robots for diversified agroecological farming could look like, be, or do remains largely unexplored.

In this paper we interrogate the push towards automation in monocultures, the lack of pull from the agroecological farming arena, and the associated critical debates on the agronomic potential as well as political ecologies that robots may imply, by exploring the potential for automating agroecology. We work with three guiding questions which address the concerns of automation from complementary angles:

- *How could robots be made to embody the practices, interactions, and concomitant forms of care of farming agroecologically?*
- *What kind of (automated) machines would be considered suitable for the socio-political embedding of agroecological farming?*
- *How should the design processes needed to induce a change of sociotechnical practices towards amplified forms of diversified agriculture (which may include automation) be envisioned?*

We explore these questions by first briefly reviewing the contextual background that led us—a farming systems scientist researching the potential of crop diversity experimentally and a cultural geographer curious whether robotization could foster ecological farming practices—to this inquiry. We then look at the guiding questions through the lens of an experimental effort at *pixel cropping* in The Netherlands, a nascent and complex intercropping method which offers a rich opportunity to understand the ways in which automation in novel agroecological, diversified cropping systems might differ from that in established industrial monocultures. Within the Dutch case, we held a series of interactive happenings which engaged practitioners from various disciplines around the challenge of how to make a pixel cropping robot. We integrated methods and learnings from the agricultural systems design literature and invited a range of systems actors in an effort to generate a diversity of approaches and responses to the same site-specific challenge. We analyze the ideas and challenges for automation that pixel cropping generated among participants in these happenings. We then explore the broader implications of the pixel cropping case, identifying key questions and possible ways forward for thinking about automation which could address the agronomic, ecological, socio-political, and design challenges of diversified, agroecological, open-field farming more generally.

6.2. Historical and conceptual background

6.2.1. Robots pushed into monocultural fields

Agricultural innovation has for the last century been generally characterized by a trend towards bigger, heavier machines (Keller et al. 2019). This trend is evident in certain directions being pursued for automation in open field farming, manifested in tools such as driverless tractors and tractor-mounted 'smart' systems and sensors. These tools often explicitly aim to reduce or eliminate the need for human operators, an objective related to both social concerns and the agronomic co-evolution of monocultures and machines. In agriculture, technological innovation is often accelerated by societal transformations which reduce the availability of farm workers and increase the need for labor efficiency (e.g. war, the abolition of slavery, changes in immigration policy, pandemics), resulting in advances in mechanization which bring particular political ecologies into being that foster large scale monocultures with concomitant environmental impacts and social transformations (Rasmussen 1982; Vandermeer 1986). When sole machines replace teams of human workers, the time required to perform cultivation tasks on a per hectare basis is dramatically reduced[3], allowing farmers to cultivate larger tracts of land by transforming "walking tasks" into "driving work" (Schmitz and Moss 2015). Farmers who invest in expensive and large machines often then face a need to specialize and upscale in order to maximize resource use efficiency, compete in economies of scale[4], and make their investments worthwhile (Scott 1999). This feedback process thus produces a particular socio-political dynamic of modernization, combining chemical and other inputs with capital requirements and

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[3] For instance, the time required to cultivate a maize crop (from soil preparation to harvest) mechanically is approximately 6-10 hours per hectare (WUR, 2009), compared to an estimate of more than 2000 hours per hectare when done by hand in a less mechanized context (Ditzler et al. 2019).

[4] The same pattern has been projected to hold for small-scale autonomous field equipment, particularly in places where safety regulations favor larger farm operations (Lowenberg-DeBoer *et al.*, 2021).

dependence on large agribusiness conglomerates, while rural and migrant communities disappear due to reduced or only seasonal, transient labor needs (Carolan 2019; Friedmann 1999; Rotz et al. 2019; Schmitz and Moss 2015).

A key factor in the drive towards large machines, automated or not, is the need to maximize the uniformity of a crop stand. Harvesting maize with a combine, for example, is only effective if all the plants in the crop stand are the same height, produce ears of the same shape, and reach maturity at the same time. Additionally, the more of the same type of plant there are to harvest in a given area, the higher the potential productivity per unit of land or labor. As such, plant breeding programs and seed suppliers, in combination with chemical inputs, have focused heavily on growth characteristics (e.g., height, crowding tolerance) that are relevant for optimizing monocultural, machine-managed cropping systems (Bourke et al. 2021; Kloppenburg 2005). Together, these factors create a mutually reinforcing feedback loop whereby cropping systems are engineered to accommodate large machines and large machines are designed to manage engineered cropping systems (Lowenberg-DeBoer et al. 2021; Miles 2019; Scott 1999).

The interlinked drivers of efficiency and uniformity lead towards the final challenge of total automation: how to do arable farming without needing human workers in the field. In addition to large driverless tractors, this challenge is being pursued through the development of small autonomous robots[5] (Relf-Eckstein et al. 2019). These go against the bigger—heavier mechanization trend, but most often still assume a monocultural approach to crop husbandry despite their potential to determine a different relationship between farming systems and machines. Open-field robotic applications come predominantly out of the precision agriculture program, which focuses on the use of technology and data to enhance resource use efficiency and maximize production through targeted, plant-level care within monocultural systems (Lowenberg-DeBoer and Erickson 2019). Here, the robotization of agricultural tasks is touted as a solution to problems of within-field variability, imprecise and overabundant agro-chemical application, soil compaction, and the high cost and low availability of farm labor (Blackmore et al. 2005; Kuch et al. 2020; Murray 2018). Applications often involve (multiple) autonomous ground units receiving and processing information from various forms of sensors (Fountas et al. 2020). Through abundant data collection, it is expected that these robots will help farmers achieve a greater measure of uniformity in their cropping systems by identifying, diagnosing, and treating plant-level heterogeneities in the field environment in a resource-efficient manner (Pedersen et al. 2006). Widespread adoption of this autonomous farming equipment would mean the shifting of manual labor demands off human farm laborers and onto robots, potentially aggravating the often racialized and gendered marginalization of agricultural laborers in some contexts (Marinoudi et al. 2019; Rotz et al. 2019; Sparrow and Howard 2020). With advances in artificial intelligence (AI), the cognitive human demand may also eventually be made optional,

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[5] For an overview (not necessarily complete) of open-field farming robots in development and on the market at the time of writing, see: https://misset.com/field-robots/field-robots/

calling into question what it means to be a ('good') farmer (Burton 2004; Driessen and Heutinck 2014).

6.2.2. Agroecological pull?

When considered as a potential systems innovation for accelerating sustainability transitions in agriculture, the lack of attention given to tools that enable agrobiodiversity demonstrates a lock-in within the monocultural system. The dominant socio-technical regime is robust, favoring developments that fit within a monoculture approach and positioning diversified cropping systems in a niche outside the boundaries of the prevailing innovation landscape (Geels 2002; Morel et al. 2020). In part, this lock-in is influenced by the fact that heterogenous field designs pose many more agronomic and technical challenges than monocultures: it is simply more difficult to mechanize or automate the management of a polyculture compared to a sole crop (Fountas et al. 2020). Additionally, an apparent lack of consensus as to what role automation should play in the transition towards a more sustainable agriculture may be impeding advances in automation for diversified cropping systems (Bellon Maurel and Huyghe 2017; Herrero et al. 2021; Shepon et al. 2018).

Within agroecology, there is an emphasis on social empowerment, equity, and sovereignty (Altieri and Toledo 2011), in addition to a strong agronomic tradition of crop diversification (Wezel et al. 2014). However, there is little academic focus on the question of how to make physical tools for agroecological practices (cf. Salembier et al. 2020). Even in a recent comprehensive overview of the research needed to apply agroecology specifically in large-scale farming contexts, written particularly from an agronomic perspective, mechanization challenges were not addressed (Tittonell et al. 2020). Although often correlated justly with specialization, upscaling, capital intensity, and other tropes of the monocultural paradigm (van der Ploeg 2021), there appears to be no fundamental reason why automated tools could not be designed to progress agroecological aims. In fact, research has shown that farmers themselves are not necessarily the ones worried about the incompatibility of technology and 'alternative' farming methods (van Hulst et al. 2020). That said, recent syntheses also show that adoption of 'smart' farming technologies is lower among 'unconventional' farmers than among 'conventional' (i.e. intensive, high-input) farmers (Bronson 2019).

Some see the lack of attention put on automation as a barrier to the amplification of agroecology (e.g. Bellon Maurel and Huyghe 2017), believing that where labor is a limiting factor, automation offers the possibility of implementing agroecological practices in new contexts and at broader scales. In painting a picture of an automated ecological farming utopia, Daum (2021) imagines that fleets of robots working 24/7 will enable farmers to adopt agroecological farming methods where high labor demands would otherwise be a constraint. For others, particularly in small-scale systems and less mechanized contexts, the manual labor demands of 'doing' agroecology are rather regarded as opportunities to foster meaningful livelihoods and community involvement, connecting humans both to the land and to each other (Nicholls and Altieri 2018;

Timmermann and Félix 2015). From this perspective, a fear is that tools such as driverless tractors or autonomous robots may undermine the intrinsic value of being a farmer, displace workers, or lock farmers into disadvantageous power asymmetries (Carolan 2019).

A hesitant stance towards technology fits into a long history of critiques questioning the societal effects of mechanization in agriculture (Fitzgerald 1991; Vandermeer 1986), and contemporary critical perspectives on the potential social and ethical concerns raised by automated farming technologies are abundant (e.g. Klerkx and Rose 2020; Rose and Chilvers 2018; Ryan et al. 2021; Sparrow and Howard 2020; van der Burg et al. 2019). Emerging key issues relate to data ownership, deskilling, exclusionary power dynamics, and shifting farmer identities (Klerkx et al. 2019). In conversation with these assessments are abundant calls for participatory and reflexive design processes in the development of responsible innovations for sustainable farming (e.g., Berthet et al. 2016; Cerf et al. 2012; Eastwood et al. 2019; Elzen and Bos 2019; Jakku and Thorburn 2010; Lacombe et al. 2018; Pissonnier et al. 2019; Prost 2021; Rossing et al. 2021). Such 'user-centered' design methods are often seen as a way to incorporate socio-political concerns into design specifications, and frequently take a systems perspective at the farm, value chain, or regional scale. Within design discussions, however, the challenge of translating the unique agronomic, ecological, and social demands of diversified cropping systems into designs for agricultural implements (let alone automated machines) is often peripheral and secondary to the design of the farming system itself (see e.g. Prost et al. 2017; cf. Salembier et al. 2020). On the other side there is an abundance of literature describing advances in open-field agricultural robotics (e.g. Bechar and Vigneault 2017; Fountas et al. 2020; Kootstra et al. 2021; Mahmud et al. 2020; Oberti and Shapiro 2016), but studies combining design processes geared towards diversified agriculture settings with automated tool specifications are noticeably lacking (Rose et al. 2021).

6.2.3. The prospect of pixel cropping

Pixel cropping (sometimes referred to as *pixel farming*) occupies a unique space of being both grounded in agroecology and dependent on technology. It is an open-field farming method in which many different food and service crops are planted together in diverse assemblages made up of small (0.25 m^2 – 2.25 m^2) crop patches ('pixels') arranged in a grid (Fig. 6.1) (Ditzler and van Apeldoorn 2018). It employs multiple agroecological techniques that increase temporal, spatial, and genetic in-field diversity (rotation, intercropping, crop mixtures), conserve soil (continuous cover, green manures), and facilitate natural pest control (habitat and resource contiguity and continuity). Pixel cropping as we describe it here was developed recently in The Netherlands following a 'Cartesian' orthogonal logic (Ditzler 2020), although it draws heavily on the principles of established agroecological methods that leverage diversity, including companion planting and indigenous intercropping practices such as the milpa or Three Sisters (Lopez-Ridaura et al. 2021; Rodríguez-Robayo et al. 2020).

Although a pixel plot is organized in a grid (for ease of management and scientific study) which resembles the pixelated field maps used to collect and present data in precision agriculture, the concepts underlying pixel cropping are not about precision. Rather, the method aims to maximize the structural diversity of the arable field, and in doing so create a production system that functions as a healthy ecosystem. Algorithmic inputs may be utilized in the design of a pixel field (e.g., following rules for which crop—neighbor combinations to encourage or avoid, or the outputs of detailed soil mapping), so in this way pixel cropping does not exclude the digitalization underpinning precision agriculture, but homogenization is not an aim. After a pixel plot is sown, what develops may appear wild and unruly compared to conventional agriculture. The high-resolution of individual pixels creates an assemblage of ecological interactions, generating multiple dimensions of habitat, resource, and functional diversity which occasion emergent properties beyond production—what Tsing (2015, p. 23-24) refers to as the "multiple temporal rhythms" and "patterns of unintentional coordination"—that can be understood as agro-ecosystem services.

Figure 6.1. A pixel cropping plot at the Wageningen University field trial on the Droevendaal Organic Experimental and Training Farm, NL in which six crops are planted in 0.5 m x 0.5 m pixels in plots of 9 m x 12 m (**a**); and a subset of the 2020 pixel field planting plan at the Lochem, NL trial in which 30 crops are planted in 1.5 m x 1.5m pixels in a 1 ha field (each color represents a different crop) (**b**)

There is strong scientific evidence that high resolution in-field diversity and small field sizes will indeed produce good yields *and* abundant ecosystem services (Fahrig et al. 2015; Sirami et al. 2019; van Oort et al. 2020), so pixel cropping is anticipated to be a promising approach for addressing emerging production and environmental sustainability aims such as those outlined in recent Dutch and European policy (EC 2020; Schouten 2019). However, pixel cropping is not yet employed outside of a limited research-oriented context, so the broader scope of the method for meeting these aims—as well as its profitability and global applicability—have not yet been explored. At the time of writing only three pixel cropping trials were known to the authors, all in The Netherlands. In part, pixel cropping's limited uptake has to do with the management demands posed by its planned and emergent complexity. Labor presents a major challenge in mainstreaming or upscaling the method, particularly in places where intensively mechanized farming is the norm, as in The Netherlands. Due to the small size of individual crop patches and the heterogeneity of the overall field layout, conventional machines cannot be used to conduct tasks such as sowing, weeding, or harvesting, meaning that currently all labor must be done by hand. There is consensus among those who have worked in pixel cropping trials that implementing the system at viable scales will require some form of mechanization, and potentially automation. However, no technologies that could work in such high-resolution and large-scale intercropping systems are yet on the market. The lack of established tools, in combination with its future-oriented outlook, positions pixel cropping as a unique case for imagining non-monocultural possibilities for automation without the influence of an already saturated solution space and within a still exploratory phase of experimentation.

6.3. Empirical approach

The discussion groups, workshops, and design challenges that this paper is based on are embedded in the PhD research project of the first author. The project was approved by the governing graduate school at the start of the PhD, and in designing and conducting the research for this paper we followed the Netherlands Code of Conduct for Research Integrity as formalized by our institutional Social Sciences Ethics Committee. The committee provides a checklist which researchers should use to determine if their research requires an ex-ante ethics review; according to these guidelines, we determined that our study met the ethical criteria and therefore did not necessitate review by the ethics committee.

The research was conducted between 2018 and 2021 in and around an existing pixel cropping field trial at the Droevendaal Organic Experimental and Training Farm located on the Wageningen University & Research (WUR) campus in Wageningen, and at an on-farm pixel cropping trial in Lochem, both in The Netherlands. Both trials are embedded within ongoing, long-term agroecological studies monitored by WUR researchers. The trial in Wageningen started in 2018 and consists of two experimental pixel cropping plots (each 9 m x 12 m) managed for scientific purposes (Fig. 6.1a) (see Juventia et al. (2021) for details of the experimental design). The Lochem trial was initiated in spring 2020 and is conducted on a working organic farm where the resident farmer uses the 1 ha pixel field (Fig. 6.1b) for both research and commercial purposes.

Centered around these two trials we explored how a diversity of practitioners from different disciplines might approach the same site-specific challenge. Drawing on methods commonly employed in agroecological research (action research (Lieblein et al. 2012), Kolb's learning cycle (Kolb 1984), the DEED cycle (Giller et al. 2011)), we designed a series of interactive happenings which progressed in topic and depth over the research period, moving from broadly positioning the question of automation within the frame of general agroecological concerns towards envisioning specific applications for robotics in the Dutch pixel cropping context. In view of the explorative character of this study, we approached the research design and analysis as an iterative process (Locke et al. 2020) in which we adapted the set-up and focus of the happenings and composition of the participants involved by drawing on observations that emerged in the process.

At the Wageningen site, we employed various interactive formats (a group discussion, a World Café-style workshop, a design challenge, and a consultancy project) to engage students, researchers, and practitioners from a range of fields in place-based efforts to explore the potential for robots to facilitate pixel cropping (Table 6.1). Most of the participants were employees and students from relevant departments of WUR, representing a range of nationalities and disciplinary backgrounds. The workshop participants also included professional designers, farmers, and independent agro-tech developers from outside the university, and the design challenge involved students from the Design Academy Eindhoven (DAE), again with international backgrounds. Both authors took extensive notes during the Wageningen meetings on the ideas that were put forward in the discussions as they occurred, in the larger gatherings with the help of a research assistant. We also archived the written and drawn outputs that were produced by participants.

In parallel to these orchestrated happenings, we also followed the progress of the self-identified agroecological farmer's first season of doing pixel cropping at the Lochem site. The farmer was collaborating with a robotics developer to test a prototype weeding robot, and we paid particular attention to the farmer's experiences with the robot and his widening effort to make pixel cropping work beyond the functioning of the robot. We conducted multiple unstructured interviews with the farmer before the growing season, and one semi-structured interview each during and after the growing season. The first author also visited the farm on several occasions, once to watch a demonstration of the robot testing its functions. We recorded the semi-structured interviews with the farmer, took notes during unstructured interviews and after field visits, and made images during field visits.

After each happening, interview, and field visit, we reviewed the archived material and inventoried the emergent themes in relation to our three guiding questions (Section 6.1), which we coded as *work*, *community*, and *design*. We then used these data as input for guiding the next happening, with the aim to broaden the imaginations being represented while maintaining a relevant focus. For example: the themes we inventoried from the discussion group were used to select the range of participants and write the prompts for the World Café workshop; the outcomes of the World Café workshop led us to develop a design challenge with students not already involved with agricultural robotics; our observations of the farmer's unanticipated challenges with the robot led us to reorient our focus around the broader context of his efforts at making the pixel farm work in practice; and our discussions with the farmer led us to ensure that an opportunity to talk with and observe someone doing pixel cropping labor was part of the student projects. Throughout this iterative process of interaction, coding, and analysis, we sought to identify variation between and within the groups that responded to or diverged from common discourses and assumptions (also ours) of what agricultural robots can or should do. To ensure that we stayed up to date with these discourses, we periodically attended agricultural robotics conferences, demonstrations, field days, and promotional events within and outside WUR; we did not collect data during these activities, but they were pivotal in helping us gain a broader view on developments in agricultural robotics in both research and commercial realms.

Table 6.1. Overview of research happenings conducted from 2018-2020 in the context of the Wageningen University pixel cropping field trials in The Netherlands, presented in chronological order.

Setting	Participants	Format	Guiding questions
Group discussion	5 agroecology-focused farming systems researchers working at WUR	Participants were posed with two open-ended questions and asked to freely discuss. Conversation topics were annotated on flipcharts.	1) What is agroecology and how do farmers implement it? 2) What would a farming robot need to do to be in line with these principles and practices?
World Café workshop	20 robotics experts, ecologists, agronomists, farmers, and designers (both from WUR and from outside the organization)	Participants were given a tour of the Wageningen pixel cropping field experiment and presented with a list of issues and desires for a diversified farming systems robot synthesized from the previous discussion group. They then rotated through mixed groups where in each session they were asked to imagine different elements of appropriate forms of automation for the pixel cropping context, culminating in a design session where the elements were integrated and presented in drawings.	1) What are the ecological, agronomic, and social requirements of a pixel farming robot? 2) How could/should these functions be integrated into an actualized design?
Challenge-based design course	20[*] second-year bachelor design students from DAE	Students were asked to respond to the idea of robots as an approach to dealing with the manual labor challenges of pixel cropping. They were first given a general introduction to the principles of pixel cropping and a tour of the Wageningen field experiment, where they interviewed the field staff responsible for conducting daily crop management tasks. They then worked independently on their design projects for eight weeks. Prototypes were presented in a studio critique setting.	1) How can the manual labor challenges of pixel cropping be solved?

Consultancy project	6 WUR MSc students	A team was commissioned to explore the outlook and design of robots for pixel cropping. Students were asked to identify the agronomic, ecological, and labor needs of pixel cropping and to design a prototype pixel cropping robot based on their findings. The team’s designs were presented in an oral presentation and written report.	1) What are the agronomic and ecological demands of pixel cropping? 2) What is the state of the art in agricultural technology to mechanize these demands? 3) What are the most promising options for integrating these functions?

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[*] The course began with 20 students split into three teams. Only one team (6 students) followed the pixel cropping labor challenge through to the end; it is that team whose work we report on in the results.

6.4. Results: How to make a pixel cropping robot?

6.4.1. Agroecology as an ethos

Our inquiry began by seeking to position the specific question of automating pixel cropping within the broader framing of diversified agriculture via agroecology, asking a group of agroecology-focused farming systems researchers to define agroecology. During this discussion, the participants focused primarily on the conceptual aspects of agroecology, rather than the science or practice components that have been defined by other scholars (see Wezel et al. 2009). Several used language to describe agroecology as a stance towards farming that believes nature should be worked with rather than against. One participant explained, farming agroecologically means using a localized approach in which you start with "what the ecosystem offers" and seek to "understand the function of each inhabitant of the ecosystem" and then design farming interventions based on nature's "template," rather than the other way around. Another participant, who was from Southeast Asia, described expressions of agroecology in her community as being linked to a religious edict prohibiting the harm of nature. Participants returned often to the theme of connectedness, in reference to agroecology being about embracing and intensifying connections—e.g., between plants and earthworms, between farmers and their soils, or between farms and communities. How participants envisioned such relationships was also characterized by a localized contextualization; despite their different cultural and geographical backgrounds, all participants referred to agroecology as being necessarily adapted to local circumstances and belief systems, resulting in different connections to be emphasized in different contexts.

The way the participants envisaged agroecology appeared to imply that to practice agroecology is to invest in the connections, both ecological and social, that root farming and food systems in local ecologies and cultures. Interestingly, we witnessed no discussion about how these values and approaches could or should be implemented in practice when participants defined agroecology. The group in fact did not talk about work at all, never addressing what it looks like to physically execute agroecological practices. More generally, discussions of the importance of farming in a way that is attuned to ecologies and the temporalities of soils and other aspects of agroecosystems do not necessarily link to the challenges of everyday embodied practice. In these discussions the various aspects of an approach such as agroecology can be better understood as describing an ethos[6], within which knowledge is a key theme, but reference to forms of mechanization (let alone automation) are not often made (Puig de la Bellacasa 2015; Sanderson Bellamy and Ioris 2017). The implications of this first discussion group suggest that an agroecological approach to automation should consider the ecological relationships and cultures

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[6] We use the term *ethos* following Van Dooren and Rose (2016) to mean not only a particular way of defining the elements, objects, and subjects the world is made up of, but also as a mood, an aesthetic, a way of narrating, and a collectively shared attitude.

motivating the material practice as equally as relevant as technical specifications, generating the question of how to inscribe an ethos in agricultural machinery.

6.4.2. Neighbors, ducks, or robots?

In the second part of the conversation with the farming systems researchers, we centered the question of possible synergies or tensions between automation and the previously described aims of agroecology. Here we noted an important difference in the focus of the discussion: when we asked about automation, participants brought up broader issues around the work of doing agroecology, which we could map onto longer-standing debates about the political ecologies of agricultural mechanization as discussed in Section 6.1. One participant (a farmer himself) reflected that during a tactile task like manual weeding, a farmer is "not just weeding" but also observing the crop, the soil, and the environment, the manual labor thus affording something more than could be gained if he did the task with a machine. On the other hand, he noted, "after three hectares, [hand] weeding is not so 'Zen' anymore." This tension between the desirable sensory—and even meditative—experience and the drudgery of doing farm labor was echoed in a subsequent discussion about the potential advantage of automation as a tool to open up time, in which participants simultaneously championed the embodied knowledge that a farmer can accrue through physical labor and acknowledged that eliminating such labor might free the mind to explore opportunities for system "redesign" (Meynard et al. 2012).

When we asked participants specifically what a robot would need to do to fit into their definition of agroecology, they focused on the role the robot might assume in a farming community, which differed between their working contexts and the social norms and investment capacities available there. The participant from Southeast Asia explained that in her community many people need work, and she would rather hire a neighbor to weed her field than employ a robot. Conversely, a participant from a Nordic country noted that he would rather avoid talking to his neighbors and therefore would welcome a robot. When asked about tasks that may not be suited to human hands, such as controlling pests in a rice paddy, the Southeast Asian participant replied that robots were still not needed because "we have ducks for that." The question of whether a robot would be regarded in particular contexts as either desirable (reducing the drudgery of labor, affording time for system redesign) or undesirable (displacing valued neighbors or ducks) could be seen as a contemporary iteration of discussions around the definition of progress in agriculture, flagging the continued relevance of long-standing calls to consider the localized social, cultural, political, economic, and ecological conditions that surround proposed technological change as well as the non-economic reasons farmers may have for pursuing particular technologies (Fitzgerald 1991; Harwood 2013; Sparrow and Howard 2020; Vandermeer 1986).

6.4.3. What should be automated?

After framing the concepts and issues underpinning the general question of automation in agroecological farming systems, we moved into the happenings targeted specifically at pixel cropping (the World Café workshop at Wageningen, the challenge-based design course with students from the design school, and the consultancy project with WUR students). Although different, the entry points of both the World Café workshop participants and the two student groups seemed to reveal an underlying assumption that all needs of the cropping system—whether cultivated or associated—should be considered as demands that the hypothetical robot might be asked to control. As such, the approaches revealed the range of technical and conceptual considerations that would need to be accounted for in order to achieve full automation of a pixel cropping system.

The participants in the World Café workshop were most familiar with the ecological concepts behind pixel cropping and the agronomic practices employed in it, and began with a broad, holistic approach focusing on factors central to understanding and maintaining agroecological cycles and feedbacks at the foundation of the pixel cropping logic (defining system boundaries, identifying performance indicators, optimizing ecological interactions). Here participants emphasized that automating a pixel field requires a whole-system approach and a complete understanding of all the complex interactions involved. Both student groups were new to pixel cropping (the design school students had generally no experience with agriculture at all) and sought to first understand more concretely what the method entailed in practice, and then created inventories describing the production cycle of all crops in the Wageningen experiment trial and the cultivation tasks required at each phase that a robot would need to assume control of.

6.4.4. Picking, shaking, cutting, de-leafing: defining functions

The three happenings followed similar trajectories in their next steps, moving from defining system boundaries and demands into discussions of how automated tools could technically meet those demands. Participants approached the task of defining tool functions from two general angles: starting with the command center in a top-down approach, and from individual tasks from the bottom up. These appeared as complementary and equally necessary elements of the pixel cropping robot design process.

In the World Café workshop, several groups discussed the decision-making functionalities underpinning the actuation of robotic equipment. Here, participants explored the possibilities to use AI, modelling, and various forms of sensing to enable autonomous decision making, leading into questions of what role the farmer would have in relation to AI-driven systems and how much autonomy should be afforded to robotic tools. A farmer in one of these design groups (the same farmer managing the Lochem trial) expressed that no matter how many sensors robots might be equipped with, he would prefer to make the ultimate decisions himself about what functions a tool performs, stating that "the farmer *is* the sensor." Robotics engineers in the same group related to the farmers' preference as a need to build into the robot "the power to overrule"—that is, the option for a human operator to override the machine's autonomy at any moment. In the agricultural robotics literature this functionality is often referenced in regards to safety, cited as necessary for situations where the robot might be in danger of harming a person or itself (Vasconez et al. 2019). However, in the workshop, the connotations of the "power to overrule" took a different slant in the context of the previously defined system demand for holistic knowledge of agroecological interactions, of which it was acknowledged that the farmer would need or want to contribute to.

Other groups at the World Café workshop, as well as the student consultancy team, took a more grounded approach to matching technical possibilities with the system demands previously identified. For example, one workshop group discussing the challenge of harvesting crops in pixel plots diagramed four possible ways a crop could be mechanically harvested (Fig. 6.2). Similarly, the consultancy team created morphological charts, a method employed in the Reflexive Interactive Design methodology (Elzen and Bos 2019), to systematically identify tools that could execute each cultivation task (Fig. 6.3). Interestingly, the consultancy team decided at this stage that automating the whole production cycle was too elaborate to solve with a single tool and chose instead to focus only on seeding and weeding cereals, the tasks they identified as the most labor-intensive at the pixel cropping field trial. The design school team came to a very similar conclusion, determining that addressing the whole production cycle with a single tool was unrealistic. Having conducted an extensive interview with the Wageningen pixel cropping field technician and carefully observing her movements as she performed various tasks in the field, the design students identified seeding cereals as the most arduous of the field operations and decided to focus on specifying the requirements for a tool that could alleviate this particular drudgery.

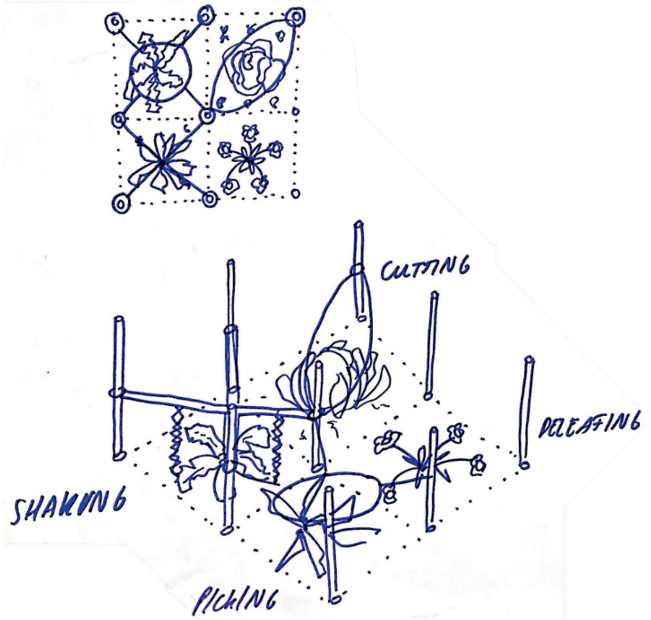

Figure 6.2. Picking, shaking, cutting, de-leafing: multiple ways to achieve the same task, illustrated by participants in the pixel cropping robotics design workshop in Wageningen, 2019.

Figure 6.3. Morphological chart created by a WUR student consultancy team for addressing the mechanical weeding function of a pixel cropping robot, 2020.

6.4.5. Integration: high-tech, low-tech?

The World Café workshop participants and student teams moved next towards the ideation phase in which functions were integrated into comprehensive designs. In each setting, we asked for visual renderings of the imagined tools. At the Wageningen workshop, participants used flipcharts to sketch out their ideas while drawing on the lists of functions and solutions developed in earlier phases of the World Café. A striking outcome of this session was that nearly all integrated designs appeared highly similar in form: most drew robots composed of a gantry frame carrying tools over a field using Cartesian navigation (Fig. 6.4). Among these designs there was some variation between groups in how they addressed the different functions of the robot, for example whether the tool rolled independently on wheels or was mounted on fixed rails, but all were described as incorporating multiple functions to automate production from seeding to harvest.

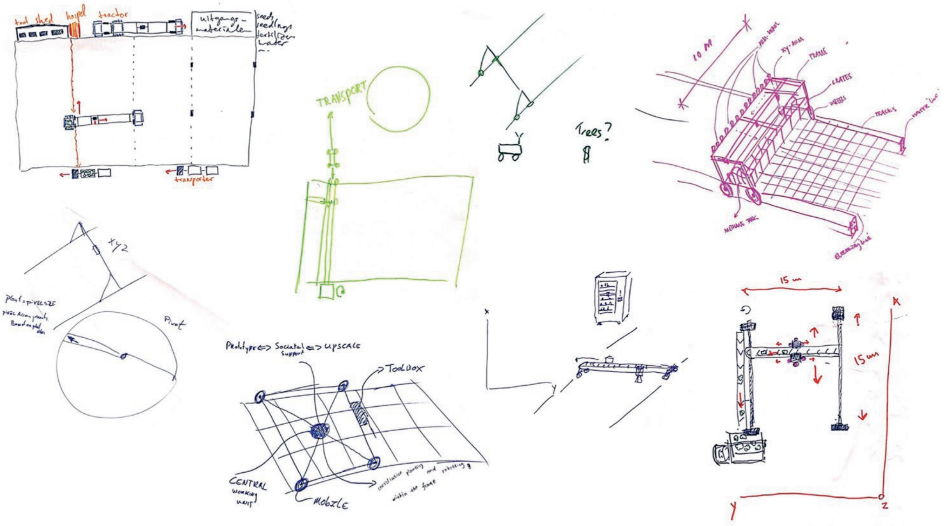

Figure 6.4. A variety of drawings produced by participants at the pixel cropping robotics workshop at Wageningen in 2019, all approaching automation through similar forms.

Students in the consultancy team tackled the integration phase by selecting options from their morphological charts and combining them to create two robot design sketches. For one version, which they called the “high-tech” model, they selected the most state-of-the-art options for each function (Fig. 6.5a). The consultancy team’s second model was designed to be more economically feasible; for this model they selected tools already commonly in use (e.g., a diesel engine instead of solar power, a hoe weeder instead of electrothermal weeding arms). The two models were presented as representative of a spectrum of options book-ended by a lower-tech but currently feasible and economically accessible tool vs. a more comprehensive tool with less established and more expensive technology but greater autonomy. The design school team took an entirely different direction, abandoning the idea of a robot altogether and instead designing analogue hand-tools. Drawing on their interview with the field technician and their observations of her movements, the design school students came to the conclusion that a simple hand-tool that could be used immediately would have a greater impact on lessening her burden of manual labor than aspirational robotic equipment. They developed a simple, two-part seeding tool and fabricated working prototypes; the tools were light weight, required no power source, had few moving parts, were simple to operate, and were ergonomically designed so a farmer could use them while standing (Fig. 6.5b).

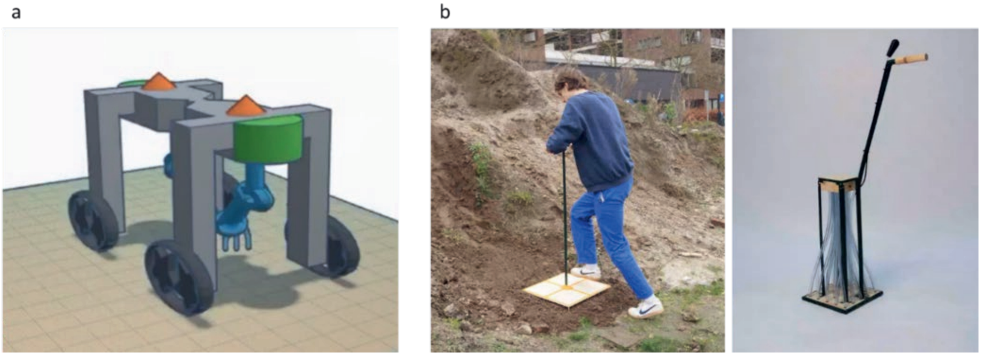

Figure 6.5. Mock-up for the "high-tech" robot model designed to seed and weed cereals in pixel plots, created by the WUR student consultancy project team, 2020 (**a**); prototypes for a two-piece analogue seeding tool developed by DAE students for sowing cereals in 50 cm x 50 cm pixels (**b**) (Objects and images in panel **b** made by Mick Thörig and Floris Meijer, 2019).

6.4.6. Shifting priorities on the farm

At the Lochem site we observed various stages of developing a pilot commercial pixel farm, speaking with the farmer at key moments in the planning, execution, and reflection of the first growing season, including practical trials with a pixel cropping robot prototype. Throughout this process we witnessed several pivotal moments during which the farmer shifted or re-formulated his approach as new challenges and unexpected outcomes presented themselves.

At the start of the season, the farmer's plan was to use a small tractor to manage the soil preparation, sowing, and planting in the pixel plot. On a visit to the farm during the growing season, we observed emerging management challenges related to these mechanization ambitions. After marking out the pixel field with the tractor, the farmer had become concerned about soil compaction and changed plans: "We started to do it with a planting machine but you had to drive through a [whole] row for maybe one or two pixels...and I didn't want to go drive the tractor all the way through the land every time." Abandoning the tractor meant doing the planting manually: "...we had to do it by hand. Every single pixel. And there was about 4,000 in the hectare. I'd say a month at least it took us to get all the plants in." The farmer deemed this an unacceptable time and labor burden and indicated he would not do it this way again in the future, later reflecting, "it was a hard time."

The farmer also intended to use a robot prototype to weed the field having arranged for a robotics developer to use his field as a testing site in exchange for weeding services. Yet the robot was not fully functional at the time when weeding became necessary, so the farmer and his team started hand weeding. Following a period of particularly hot and dry weather the farmer observed that the seedlings in the weeded pixels fared worse than those in the un-weeded pixels: "We cleaned a few pixels during the warm days, but the crops, those ones died. Too warm, the ground dried out." Following this observation, he decided to discontinue the hand-weeding efforts. No further weeding was done during the growing season, except for small test areas when the robot eventually arrived.

We next visited the Lochem farm to watch one of the robot trials, during which we saw the farmer walking behind the robot as it weeded a row of pixels (Fig. 6.6). In part he appeared to be observing how the machine operated, but he was also cleaning up after the robot. The robot was imprecise and missed weeds periodically, which the farmer then pulled himself. This form of monitoring the robot, or even collaborating with it, was a middle ground we had not seen explored in the other design projects and discussions. In an interview a few weeks after the robot's weeding demonstration, the farmer reflected that developing the weeding function of the robot prototype was in his opinion no longer a priority stating, "I'm slightly changed now, the way I see crops are growing now, I'm not too bothered with weeds anymore." The farmer expressed that he felt the assistance of the robot should be instead directed towards alleviating the more essential and time-consuming task of planting crops in the field.

Figure 6.6. The Lochem farmer walks behind a prototype weeding robot and pulls out the weeds it missed, summer 2020.

During a mid-season interview we discussed the broader implications of automation. Asking whether the farmer saw the robot as a threat to his livelihood or to his approach as a self-identified agroecological farmer, he replied that he would welcome a tool that would help to alleviate the monotonous farming tasks that required a lot of time but little intellectual input. With the freed up time, the farmer reasoned, he would be able to devote more energy to walking through his fields, an activity which he both enjoys and which helps him to learn about his farming system and make more informed management decisions: "I'd rather be in the fields and look at crops and decide what to do instead of sitting on the tractor...looking at plants, touching plants, taking out a plant and looking at the roots...I walk through the field now and I'm really happy." In this way, we understood that the automation of mundane tasks would allow him to deepen his connection to his farm and the natural ecosystem within which it is embedded and would not occasion a change in his identity as an agroecological farmer. This rationale echoed closely what some of the farming systems researchers had discussed previously regarding a desire to both foster connection and to open up time for thinking, which the Lochem farmer indicated could both be enhanced—not diminished—by the assistance of automation.

After the growing season had concluded, we again met with the farmer to discuss his reflections on the trial. During this conversation we focused on his shifting perspectives regarding the value of weeding and the tasks he would like to see a robot take over. Here, he stuck to his conviction that weeding was no longer necessary and emphasized his desire to instead have a planting robot. Additionally, the farmer had conducted a post-season survey with customers who had rented pixels in a community supported agriculture (CSA) scheme during the 2020 season. Many of the CSA members had indicated that they wished they had had more opportunities to interact with the pixel farm and participate in cultivation activities. Thus, in addition to asking the robot developers to focus on planting and sowing, the farmer had decided to try hosting a series of open days at the start of the next growing season during which the CSA members could plant their own pixels. The farmer anticipated that the labor reduction afforded by the combined efforts of the CSA members and the new robot functions would make the field preparation manageable enough to engage in a second pixel cropping trial season.

6.5. Discussion: beyond the dream of total automation

Through a series of exploratory research inquiries, we asked people from different backgrounds to imagine automated tools for pixel cropping, using pixel cropping as a particular translation of agroecology and a stand in for a broader range of diversified alternatives to monocultures in industrialized contexts. While we had previously identified the predominating approaches towards automation in open-field farming systems—each leading to reinforcement of a monocultural paradigm, with total replacement of humans by machines as a central goal—what arose in these happenings was a wider range of possible approaches and imagined relations between humans and robots. The spectrum of possible directions in which to take robotics that came out for pixel cropping highlighted different aspects of a set of interconnected dialogues: on the ideals and practices of agroecology, the socio-political concerns of mechanization, and how to approach design processes for sustainable agricultural transitions. Each of these suggest different ways of understanding and imagining automation for agroecological farming systems.

6.5.1. Can an ethos be automated?

In the robotics engineering literature, the operational management of farming systems is described as an iterative loop which involves an actor (farmer or machine) receiving information, processing that information, deciding how to take responsive action, and then actuating the task. It has been considered that there are four levels to which parts of this loop can be automated, book-ended by full human labor and total automation (van Mourik et al. 2021). What we saw come out of the World Café workshop, and to some extent also the consultancy project, were robot designs that largely conformed to the mainstream aspiration of total automation as well as the homogeneity of form generally adhered to in robotic equipment coming out of precision farming programs. In both settings, participants envisioned tools which were meant to fully replace human hands in the execution of a predefined list of tasks, providing evidence that the dream of total automation exists not only in the monocultural paradigm, but also in the minds of those confronted with a polyculture. Despite staying within a limited range of robot forms, a key deviation from dominant automation narratives was evident in how participants in our happenings imagined the information processing and decision making stages within the operational management loop.

Through our happenings we learned that to create a fully automated pixel cropping robot implies not only the development of a wider range of plant recognition and actuation functions (e.g., sowing, weeding, and harvesting multiple different crops[7]), but also programming into a robot the ethos of agroecological farming which draws on a multiplicity of ways of knowing soils, plants, and other (un)invited flora and fauna, their functions, and interactions (Tittonell et al. 2020). Bringing agroecological ways of knowing and responding to plants into the robotic imagination opens space for new thinking about how crops are related to and interacted with in the field—whether by humans or by machines, or newly imagined combinations of the two—that has not yet entered the mainstream monoculture paradigm. In monocultures, where crops are approached as passive objects awaiting manipulation, receiving information, processing it, and deciding how to act is a mono-linear process which leads to a straight-forward management action. In a diversified cropping system like a pixel farm, which leverages ecological controls rather than external inputs, distinctions inherent in the linear input—output and binary crop/weed monocultural approach become blurry and often irrelevant. The system itself becomes an active participant in the farming activity as interactions such as those between crops and insects emerge and self-regulate (Tsing 2015). As such, the stages of the operational management loop become much more complex, the decision making fuzzier, and the range of possible actions more extensive. To accommodate this fuzziness, design might need to be conceived not as leading to a particular robotic device with functionalities which match tasks predefined in an operational management loop, but as part of a process that reconfigures and rethinks relations while maintaining an ongoing openness to adapt and learn from these relations.

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[7] Existing research projects have channeled entire multi-year grants towards the development of tools that can identify and remove a single species of weed from between a single species of crop planted in monocultural and row-based field layouts (e.g., Nieuwenhuizen et al., 2010). To move towards a system in which a robot could encounter any plant, growing anywhere, and then determine based on its identity whether or how to engage with it, would require advanced applications of visioning, sensing, and machine learning not yet achieved.

Following Escobar (2018, p. x), we can think of design as ontological: bringing about particular ways of being, doing, and knowing. Fully automating agroecological practices would imply that robotics developers would have to make choices about what the essential interactions are within the system (e.g., pest—natural enemy) that should be optimized or facilitated, and then translate this knowledge into articulated actions supported by the technology. If the final phase of automation is to be understood as human-free, the robot would have to be equipped with the ability to learn and make these decisions in real time, a prospect which triggers new questions about what ontologies robots should be taught to adopt (Legun and Burch 2021), and the ethical implications of these choices (Ryan et al. 2021; van der Burg et al. 2019).

In a fully automated scenario, success presumes that the human manager only relates to the robot and the data it generates and not to the farm field directly, calling into question what trajectories for farming knowledge and farmer identities such tools may perpetuate or precipitate (Carolan 2020; Rotz et al. 2019). A recent news story explained that farmers who had acquired a weeding robot could drop the robot off at the field and then happily sit back and watch television while the machine did the work for them (Radersma 2020). As this story suggests, the type of tacit, sensuous knowledge a farmer gains by spending time in the field risks being replaced by data-mediated knowledge when farming operations are automated (Carolan 2020; Kuch et al. 2020). We heard this concern raised by participants in the agroecology discussion group. Yet, the Lochem farmer later provided an alternative and more nuanced view in which the desirable sensory experience of farming could be separated from the drudgery of doing monotonous tasks. This distinction offers an interesting new way to think about the space automation might occupy—and open up—in the agroecological farm operations management cycle that would not further disconnect a farmer from their fields but instead afford the time to engage other forms of knowledge and care (Puig de la Bellacasa 2015; Smith and Fressoli 2021). Being a farmer who uses robots could mean a shift in how farmers self-identify or are identified by peers (Burton 2004), but the Lochem farmer's story suggests it does not have to mean a shift from being a tractor driver to being a computer controller (or TV watcher). Engaging in the forms of robot-enabled care the Lochem farmer described could also become associated with what it means to be a 'good' agroecological farmer in a post-productivist paradigm (Burton 2004).

6.5.2. Working with robots, or going without

The outcomes of our pixel cropping inquiry suggest that there may be room for achieving novel aims within the bounds of dominant automation narratives. We saw evidence that the types of relations between farmers, ecologies, and communities that "technoscientific futurity" (Puig de la Bellacasa 2015) might occasion could be beneficial and not necessarily contrary to agroecological care, as unfolded in Lochem. There, we saw the farmer envision a type of agroecological connection that is both enabled by automation and that allows for cultivating an ethos—one that values production but at the same time allows for other ways of relating to crops, soils, ecologies, and the wider community. This vision transcends the opposition highlighted by other scholars in which care oriented around vital practices and experiences is considered to be in danger of being "discounted, or crushed, by the productionist ethos" (Puig de la Bellacasa 2015, p. 708). Additionally, centering crop husbandry as an act of managing ecological relations provides a profoundly different way of thinking about farming—and enabling technologies—within large-scale production environments (Sukkel 2020). These outcomes recall other work suggesting that maintaining some of the tested tropes of monocultural farming may provide a conceptual and operational bridge for farmers reassembling their systems towards sustainability goals (e.g. strip cropping, Ditzler et al. (2021b)) or technology transitions (e.g. "robot-ready" apple orchards, Legun and Burch 2021).

We also observed the limits imposed by monocultural thinking and saw evidence that a loosening of definitions may be needed in the case of automating agroecology. First, broadening the notion of automation could allow room for blended models of engagement that may be more locally appropriate than full robotic control (and potentially more accommodating to safety regulations, see Lowenberg-DeBoer et al. (2021)). When the Lochem farmer walked behind the weeding robot picking out weeds it had missed, he demonstrated a human—robot collaboration, what could be viewed as a 'co-bot' scenario, that goes beyond the "supervised control" described by van Mourik et al. (2021). This type of collaboration has given rise to a number of debates regarding the role of technologies as replacers or collaborators for humans (Ryan et al. 2021), and philosophical questions of who is adapting to or assisting who (Bissell 2021). Smith and Fressoli (2021) provide a useful conceptual framework for thinking about "post-automation," where encouraging a plurality of engagements with technology could provide an alternative to an essentialized future for automation. Human—robot collaboration however, is not well explored in the agricultural robotics literature (Vasconez et al. 2019). Rather, the farmer's position is more commonly envisaged as described by Lowenberg-DeBoer et al. (2021, p. 11) as sitting "in a vehicle at the edge of the field working on a computer". Second, expanding the view of what is considered a "radical redesign" (Altieri et al. 2017; Hill and MacRae 1996; Pissonnier et al. 2019) could provide necessary room for using familiar or 'old' tools in new ways (Stuiver 2006; van der Veen 2010). In different contexts the radical option might emerge in an unpopulated middle ground: as an opportunity to engage more deeply with community (as on the Lochem farm), as a change of practices mid-season (as the Lochem farmer did with weeding), as embracing the 'low-tech' (as the design school students did), or as commons-based peer production (Smith and Fressoli 2021) exemplified in projects like the French collective L'Atelier Paysan (Salembier et al. 2020), the "Slow Tools" movement in the United States, and the international open-source exchange platform Farm Hack.

The variety of appropriate ways in which we saw automation could be used for agroecological aims reflects the locally embedded nature of agroecology, and its emphasis on diversity—not only of crops but also of system actors. In our happenings, we witnessed a range of tool designs emerge from the same context but devised by different types of practitioners, highlighting the potential for the structure and content of design processes to steer outcomes towards different visions for automation. A diversity of design processes and designers is therefore likely essential to address the multifaceted design needs of automated farming futures, needs which will vary in relation to the context-specific political ecologies that automation may precipitate. Locally-adapted and diverse design processes could help to avoid that the limited values and norms of homogeneous designers dictate a perpetuation of business-as-usual (Bronson 2019; Escobar 2018), that valued human or non-human actors are displaced (Schmitz and Moss 2015), or that one-way technology development fuels a trajectory towards a robot-managed mega-monoculture dystopia (Daum 2021).

Our findings also suggest that an iterative and reflexive design—test—learn—redesign process, as is commonly used in farming systems design and innovation approaches (e.g. Rossing et al. 2021) is relevant not just for the design of production systems, farms, or landscapes, but also for the farming implements themselves (Rose et al. 2021). On the Lochem farm, the prospect of using a robot to facilitate pixel cropping had initially led the farmer to experiment with a novel and risky form of farming, yet as the season progressed, we observed that the interplay between the not yet fully realized robot and emerging complexity of the cropping system in turn led to surprising lessons about not needing certain presumed robotic functions. This example highlights the importance of making room for what Meynard et al. (2017) and Salembier et al. (2020) have called "coupled innovations", in which the design process is shifted from aiming to achieve a singular end goal (how to automate system *x*?) and rather towards a feedback process driven by the underlying ethos of the desired system (how to facilitate the processes and outcomes we want?) for which the right implement may or may not be a robot, or might involve combinations of humans, manual tools, and forms of automation.

6.6. Conclusions

This paper raises questions on how to realize automation within agroecological cropping systems, given that the predominating directions for automation playing out in the open-field agricultural sphere are aimed not at amplifying diversified cropping systems but at enabling the industrial monocultural paradigm to persist in the face of shifting societal demands and economic logics. Through the case of pixel cropping, we explored what might come out when various actors considered automation and designed tools specifically for an agroecological paradigm in which complexity is embraced, ecological cycles are fostered, and the boundaries between binaries such as crop/weed and labor/fulfillment are blurred. What emerged was a diversity of approaches and imaginations for automation, which ranged from full automation, to collaborative modes, to fully analogue tools. From these examples we learn that automating agroecology will require the same situated and diverse range of approaches and actors that is at the foundation of the agroecology ethos, and therefore a rethinking of what automation might mean in different contexts.

Drawing on the findings of the pixel cropping case, we propose to engage with the notion of automation for agroecology as a dynamic range of context-dependent options and directions, rather than an all-or-nothing binary. We posit that this will be more realistic regarding technical feasibility, more accommodating to the ethos of agroecology, and more malleable to the diversity of socio-political contexts within which new farming technologies will land. In the design of (partially) automated tools, expanding the notion of automation would require envisioning design not as a linear development through which an object is created following a preconceived blueprint of tasks to be relieved from human hands. Rather, design could be conceived as a place-based, iterative, and dynamic feedback process involving designers, researchers, farmers and farm workers, non-human system residents, and other locally relevant groups, thereby creating space for (radical) middle ways to emerge. For researchers and designers, we posit that such a process should start with seeking to understand both the ecological and human characteristics of the agroecological system being designed for, rather than starting with monocultural assumptions and seeking to fit them onto diverse cropping systems. Integrating the diverse knowledges and embodied practices of agroecological farmers and farm workers will be key for re-orienting automation away from the constraints of monocultures, and potentially towards more technically achievable applications that can respond to dynamic conditions and incorporate ongoing learning processes. For practitioners and researchers of agroecology wary of automation, a more expansive view of what automation could mean in different circumstances might allow new labor solutions to emerge, in conjunction with new roles and experiences for practitioners and their communities, potentially creating opportunities for wider uptake of agroecological modes of crop care.

Acknowledgements

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Chapter 7

Taking pixel cropping to the museum

Early in the course of my PhD, my promotor came to my desk and asked if I would mind giving a tour of our pixel cropping experiment to “a bunch of architects.” The architects turned out to be Rem Koolhaas and his associates from AMO (the research branch of the architecture firm OMA), and what followed was a multi-year project of becoming increasingly involved in their development of *Countryside, the Future*, an exhibition presented at the Solomon R. Guggenheim Museum in New York which was on view from February 2020 to February 2021. The experience of collaborating on a section of the exhibition was central to my research inquiry—offering an invaluable process of shaping and reshaping, adding and subtracting, testing and adjusting what would become the contents of this thesis. And yet my engagement in the project does not show up in the peer-reviewed scientific articles that constitute the formal output of the research. My aim here is to valorize the *Countryside* project and its role in my research by giving thesis space to the story of taking pixel cropping to the museum.

By travelling to the museum, pixel cropping became more than a field trial. It evolved into a way of looking at the future of agriculture, of telling a story about different future imaginaries: a boundary object rich with metaphor and subtext and openings to new (scientific) questions. In this interlude to the research chapters, I first reflect on the process of taking pixel cropping to the *Countryside* and how it impacted my PhD research, and then present a visual essay of the narrative we exhibited in the museum.

7.1. A travelling field experiment

In short, the *Countryside* exhibition examined "radical changes in the rural, remote, and wild territories collectively identified as "countryside," or the 98% of the Earth's surface not occupied by cities" (www.guggenheim.org/exhibition/countryside). The show was designed around chapters, each of which explored a different thesis about how these radical changes could be understood, with examples from particular territories. Chapters were developed collaboratively by diverse teams of researchers, artists, designers, and writers. Themes ranged from historical conceptions of utopia, land reform campaigns, migration, nature conservation, village life, permafrost, railways, gorilla politics, tourism, Cartesian space, oceanic wilderness, and more.

Central to the *Countryside* narrative was the role of agriculture. The exhibition team wanted to highlight the innovative Dutch agricultural sector as an illustration of the way agriculture is shaping and being shaped by the countryside and were looking for examples of Wageningen University research that could be showcased. It was in this search that the AMO team landed at my pixel cropping trial, reportedly after getting quite bored of seeing yet another automated greenhouse. The pixel farm quickly won over the architects with its juxtaposition of careful scientific design and apparent ecological autonomy (what Koolhaas aptly termed "urbanism for vegetation") and after a few repeat visits, the team officially invited pixel cropping—and me—onboard the *Countryside.*

Through a process of working in a genuinely transdisciplinary format to present the story of pixel cropping to a wide public audience, I was exposed to the kind of conditions that Scheffer et al. (2015) argue are those that enable dual thinking[1] in scientists, namely 'diversifying inputs' and taking on 'the arts as a partner.' Diversifying inputs is about expanding the scope of disciplines that you interact with—the mind being exposed to remote lines of thought allows for novel connections to formulate. Taking on the arts as a partner creates space for these novel connections to take shape in new formats and arrangements that extend beyond the communicative modes of academia.

My role in the project was to help develop a (visual) story about the competing agro-futures emerging in the Netherlands by drawing on cropping systems research conducted at Wageningen University, for what would become the final chapter of the exhibition. Pixel cropping would be positioned as the conclusion to a wider agricultural narrative, and a connecting node in a web of other research seeking to expand on the more commonly told story of Dutch agriculture—the sterilized and soil-less greenhouses of Westland (see e.g. Viviano (2017)). A key aim in developing the new narrative was to link the development of reductionist, control-driven technologies and the holistic, ecology-based approach of pixel cropping via their shared 'Cartesian' conceptual roots while simultaneously juxtaposing the directions as leading to very different potential agricultural futures. Figure 7.1 shows some of the thought process that went

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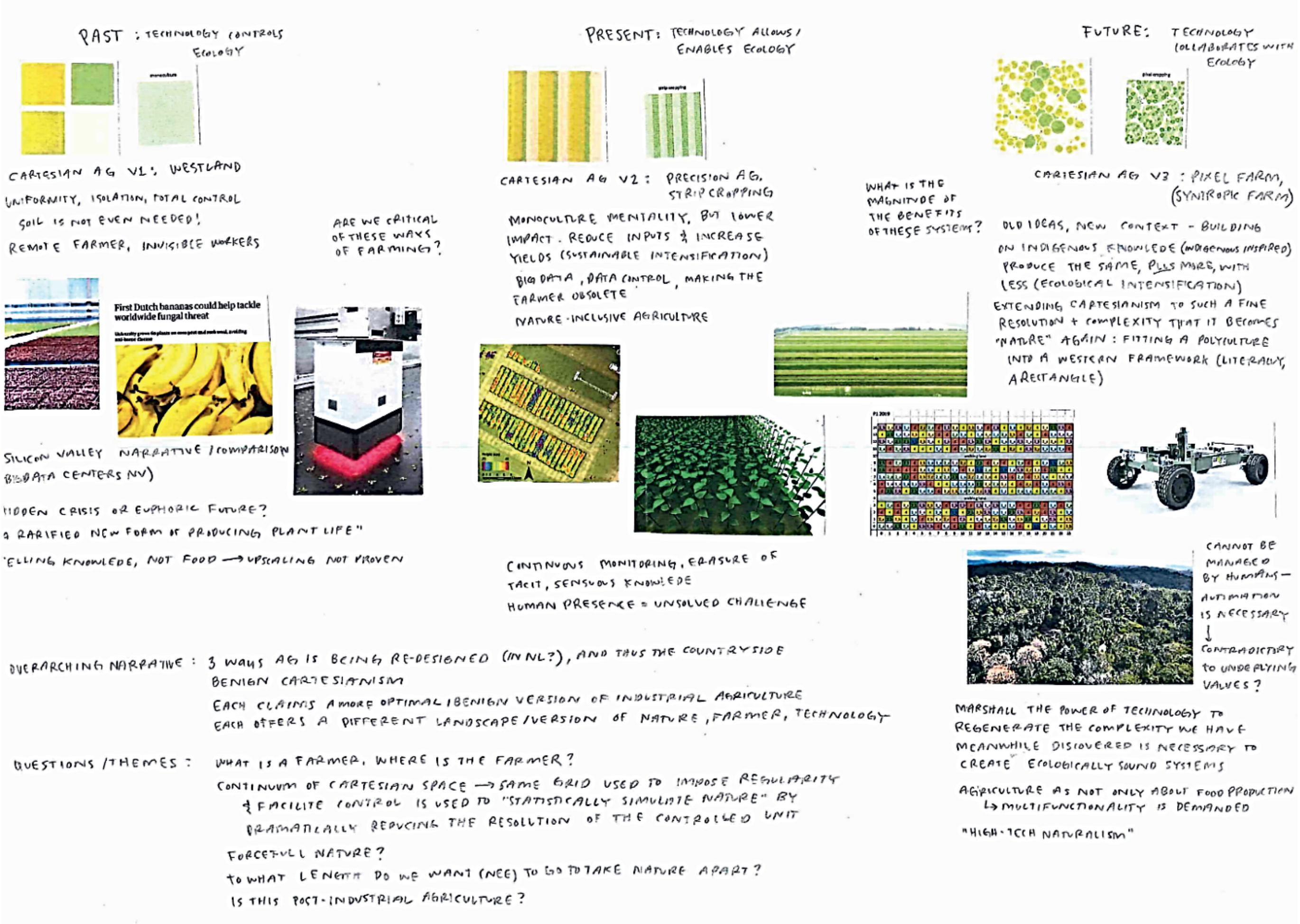
[1] 'Dual thinking' here refers to the ability to engage both systemic reasoning and intuitive, associative thought processes (Scheffer et al. 2015).

into developing these links: a visual outline summarizing a working version of the competing agro-futures narrative we later presented in the exhibition. Here we delineate three ways agriculture has been / is being (re)designed in the Netherlands based on scientific pursuits, utilizing an earlier version of the mono—strip—pixel framework I elaborate in this thesis.

In seeking to develop this new narrative, we followed a methodology which aimed to facilitate novel connections between disciplines and to link artistic and scientific efforts by creating conditions and openings for creative associations to emerge and develop (Scheffer et al. 2015; Westley and Folke 2018). We centered pixel cropping as the connecting subject, and we used the Wageningen pixel cropping field trial as a discursive staging ground for learning about the different kinds of knowledge that goes into designing and interpreting such an experiment, seeking to find connections between its many possible angles of interpretation. Over the course of two years, we invited a wide range of experts and practitioners to visit and interact with the experimental site and concepts, and through these interactions gathered a broad array of (scientific) perspectives that informed and were informed by pixel cropping and its approach. Several of these happenings became the foundations of Chapter 6. Others fed directly into the *Countryside* show in the form of visual and narrative content. A key example of this was when we worked together with a soil biologist, a functional-structural plant modeler, a cultural geographer, landscape architecture students, and video artists to create a short film for the museum that explained the concepts, prospects, and open questions of pixel cropping, bringing together the discrete disciplines in a format that combined science with storytelling, poetry, and creative visuals. Making the film was an intensive process of continually finding new ways to explain, understand, and communicate the experiment's hypotheses, underlying scientific assumptions, and results.

Figure 7.1. (Facing page) Visual outline summarizing a working version of the narrative we developed for the Dutch agriculture chapter of the *Countryside* show. The outline was co-created by me and Clemens Driessen, in conversation with the AMO *Countryside* team and with input from Nahid Tabrizi, Dirco Kok, and Dirk van Apeldoorn (April 2019).



PAST : TECHNOLOGY CONTROLS ECOLOGY

CARTESIAN AG V1: WESTLAND

UNIFORMITY, ISOLATION, TOTAL CONTROL

SOIL IS NOT EVEN NEEDED!

REMOTE FARMER, INVISIBLE WORKERS

ARE WE CRITICAL OF THESE WAYS OF FARMING?

First Dutch bananas could help tackle worldwide fungal threat

SILICON VALLEY NARRATIVE / COMPARISON BIGDATA CENTERS NV)

IDDEN CRISIS OR EUPHORIC FUTURE?

A RARIFIED NEW FORM OF PRODUCING PLANT LIFE"

ELLING KNOWLEDE, NOT FOOD → UPSCALING NOT PROVEN

PRESENT: TECHNOLOGY ALLOWS / ENABLES ECOLOGY

CARTESIAN AG V2: PRECISION AG, STRIP CROPPING

MONOCULTURE MENTALITY, BUT LOWER IMPACT. REDUCE INPUTS & INCREASE YIELDS (SUSTAINABLE INTENSIFICATION)

BIG DATA, DATA CONTROL, MAKING THE FARMER OBSOLETE

NATURE-INCLUSIVE AGRICULTURE

CONTINUOUS MONITORING, ERASURE OF TACIT, SENSUOUS KNOWLEDE

HUMAN PRESENCE = UNSOLVED CHALLENGE

WHAT IS THE MAGNITUDE OF THE BENEFITS OF THESE SYSTEMS?

FUTURE: TECHNOLOGY COLLABORATES WITH ECOLOGY

CARTESIAN AG V3 : PIXEL FARM, (SYNTROPIC FARM)

OLD IDEAS, NEW CONTEXT - BUILDING ON INDIGENOUS KNOWLEDE (INDIGENOUS INSPIRED)

PRODUCE THE SAME, PLUS MORE, WITH LESS (ECOLOGICAL INTENSIFICATION)

EXTENDING CARTESIANISM TO SUCH A FINE RESOLUTION + COMPLEXITY THAT IT BECOMES "NATURE" AGAIN : FITTING A POLYCULTURE INTO A WESTERN FRAMEWORK (LITERALLY, A RECTANGLE)

CANNOT BE MANAGED BY HUMANS — AUTOMATION IS NECESSARY
↓
CONTRADICTORY TO UNDERLYING VALUES?

MARSHALL THE POWER OF TECHNOLOGY TO REGENERATE THE COMPLEXITY WE HAVE MEANWHILE DISCOVERED IS NECESSARY TO CREATE ECOLOGICALLY SOUND SYSTEMS

AGRICULTURE AS NOT ONLY ABOUT FOOD PRODUCTION
↳ MULTIFUNCTIONALITY IS DEMANDED

"HIGH-TECH NATURALISM"

OVERARCHING NARRATIVE : 3 WAYS AG IS BEING RE-DESIGNED (IN NL?), AND THUS THE COUNTRYSIDE
BENIGN CARTESIANISM
EACH CLAIMS A MORE OPTIMAL / BENIGN VERSION OF INDUSTRIAL AGRICULTURE
EACH OFFERS A DIFFERENT LANDSCAPE / VERSION OF NATURE, FARMER, TECHNOLOGY

QUESTIONS / THEMES : WHAT IS A FARMER, WHERE IS THE FARMER?
CONTINUUM OF CARTESIAN SPACE → SAME GRID USED TO IMPOSE REGULARITY & FACILITE CONTROL IS USED TO "STATISTICALLY SIMULATE NATURE" BY DRAMATICALLY REDUCING THE RESOLUTION OF THE CONTROLLED UNIT
FORCEFULL NATURE?
TO WHAT LENGTH DO WE WANT (NEE) TO GO TO TAKE NATURE APART?
IS THIS POST-INDUSTRIAL AGRICULTURE?

These types of collaborations were central to what made the *Countryside* project so important for my PhD research. Their contributions manifested in two key ways. First was the way that working with such a diverse team of people expanded my view of what qualifies as 'science communication.' When I wrote the research chapters of this thesis, I was bound to following the rules and norms of scientific writing, and in doing so produced a particular kind of communication recognizable by the scientific community: peer-reviewed articles. This process is valuable but also limited; the audience that can be reached with a disciplinary work of academic literature rarely extends beyond that discipline's academic community. The kinds of questions a research article asks and answers are also very different than those an artist or a gardener or a poet ask and seek to answer. Working on the *Countryside* show, I was confronted with very different kinds of questions than I was taught in my scientific training to work with. An excerpt from Koolhaas's essay *?* in the *Countryside* catalog gives a taste of these:

> Now that we can separate plants from the ground, isolate them from the sun and other, "natural" givens, can we not proceed beyond plants? Why do we still bother with plants?
> Does nature now live in universities?
> Should plants live in the equivalent of the smart city?
> Can you be natural and artificial at the same time?
> Do "new" plants grow best when they have fewer experiences, less memory? Are used to perfection?
> Or do they need challenge?
> Or should they grow next to each other?
> Is there mutual, interspecies benefit? Is there urbanism for plants?
> Can plants be maintained by swarms of miniature robots?
> Is a gardener nature's helper or tormentor?
> If we want to eat, are we the tormentors?
>
> (Koolhaas 2020, p. 343-344)

As a PhD candidate, training in science communication often comes packaged as an exercise in explaining your research to a 'lay audience'—the ubiquitous assignment being to "explain your PhD to your grandma," following the (flawed) assumptions that grandmas do not know much about science and that science communication is about dumbing down your vocabulary. Much more valuable, I think, would be the assignment to explain your research to an architect—not because architects know little about science (I believe they know a great deal), but because their disciplinary conventions about how to ask questions and communicate answers are very different than, e.g., an agricultural systems researcher. Communicating across disciplines requires adopting totally new perspectives and connecting remote lines of thought—a process which I found to add more depth of understanding and novelty of ideas than the exercise of simplifying my storyline.

The second key contribution of the collaborative *Countryside* process to my PhD was the deep reflection it afforded. When confronted with trying to explain to an architect why the pixel field was designed a certain way or to a climate journalist what the experimental results implied for global food production, or when being asked by a filmmaker to write a poem about my research, I had to reflect on the work in ways I was not used to. Reflection in academia usually arrives in the final paragraphs of a scientific article, where the norm is to offer a brief take on what the shortcomings of the research may have been. In agricultural research and particularly agronomic field studies, these paragraphs rarely extend beyond surveying the ways the experimental design could have been improved, noise in the data reduced, or more indicators that should have been measured—you will have read several of these paragraphs in Chapters 3-6.

More recently, learning and reflection processes within research and innovation projects are becoming a subject of study themselves (e.g. Burch and Legun 2021), with calls to build reflexivity into project methodologies (e.g. Rossing et al. 2021). Engaging with the *Countryside* community, I found that the reflections prompted by the transdisciplinary setting offered something completely different than what could be achieved 'in-house.' Broadening the audience of my research from a narrow academic community to anyone who might walk through the doors of the Guggenheim Museum invited me to anticipate a wider range of possible impact. Doing so meant looking beyond the statistical outputs of my work and reflecting on its deeper conceptual foundations, assumptions, and non-quantifiable results: *What thought frameworks led us to design the experiment in this way? What types of knowledge does this experiment produce, and for whom? Under what cultural conditions is this work relevant?* Critically reflecting in this way expanded both the scope of the work and my understanding of it. Ultimately, this expanded view became the framework for the General Discussion (Chapter 8) of this thesis.

7.2. Pixel cropping, the future?

In the following pages I take you through the narrative I contributed to for the *Countryside, the Future* exhibition as it was installed in the Guggenheim Museum. The show was much larger—here I present the storyline that led a viewer from the museum entrance to the pixel cropping display. Images are my own, unless credited otherwise.

The narrative began before you entered the museum. Outside the building a visitor would encounter a sealed indoor growth chamber, lit by pink lights, growing tomatoes without soil.

Adjacent to the tomato container, a top-of-the-line Lamborghini tractor welcomed visitors into the museum entrance. The tractor could be operated without a person in the driver's seat, remote controlled via iPad.

Arriving at the top ‘floor’ of the museum, having absorbed the majority of the exhibition, a visitor would enter the agriculture chapter. First on view was a satellite image of precision farmed fields in the Great Plains, USA. Data from the satellite enable the hyper-efficient management of vast fields of genetically identical crops. (Satellite image by Satshot, installation view by David Heald for AMO/Guggenheim)

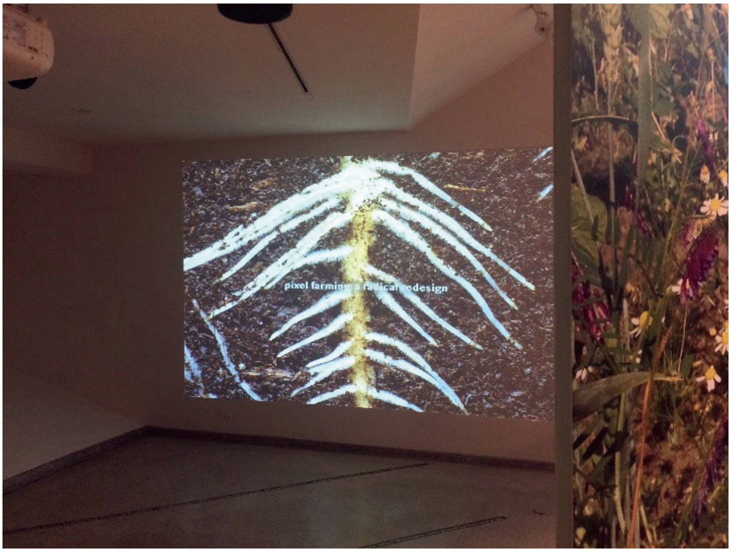
Around the corner, the pink grow lights made a reappearance in a panel showing a growing facility at Koppert Cress in the Westland horticultural region of the Netherlands, where growth conditions are sterilized, optimized, and automated. Even biocontrol agents are highly controlled, brought in and housed in artificial ‘hives.’ (Image by Pieternel van Velden for AMO/Guggenheim)

Facing Westland was installed an automated plant phenotyping machine known as the PhenoMate, used by researchers at Wageningen University to monitor the gridded arrangement of nearly 1000 individual plants, 24/7. Individuals who photosynthesize more perfectly than others can be bred and multiplied, with the aim to improve the most fundamental process of production. (Image by Laurian Ghinitoiu for AMO/Guggenheim)

Moving past the PhenoMate, a viewer would encounter a field map for a pixel cropping plot at Wageningen University (one of the plots from which data were collected and analyzed in this thesis). The map showed a grid of squares, color- and number-coded to the crop planted there, arranged in a ‘Cartesian’ coordinate system. Having just seen the gridded fields of precision farming and the CNC-like plant scanner, the viewer was invited to see something familiar, making a visual link to agro-futures that are about precision and reduction.

Projected on the wall opposite the pixel cropping field map, a film told the story of the pixel cropping concept—the need for an antidote to monocultural farming, its conceptual inspiration of indigenous companion planting techniques, the mysteries of root interactions, its invited ground beetle inhabitants, the unglamourous practicalities of labor, and the scientific efforts to monitor the system.

The film highlighted the problems of mechanization and upscaling—if industrial farming tools don't work for pixel cropping, how will the method become a viable alternative to large-scale monocultures? The narrator posits that new tools will need to be created, and reads a poem in which she dreams about what life as a pixel farming robot might be like.



Looking both above and below ground, the film offers a view into a different agro-future: one where plants and insects cohabitate and thrive, where crop/weed and nature/(agri)culture dualisms are rejected, where relations and difference are embraced. The film asks the viewer to imagine what a radically different future for agriculture could look like.

Turning the corner, a visitor would arrive at the conclusion: opposing the ordered field map, the back of the same panel showed the Wageningen pixel cropping trial in full bloom. The field looks wild and lush, almost unrecognizable as a production system. In front of the panel, a prototype farming robot—Prospero the Robot Farmer, developed by David Dorhout of Arcadia Tractor Corp.—stood poised as if waiting to enter the pixel field.

Chapter 8

General discussion

And what I really want to know is this
Are things getting better
Or are they getting worse?

Laurie Anderson, Same Time Tomorrow (1994)

8.1. Mono, strip, pixel, *x*

8.1.1. Does it work?

In the previous chapters I presented four interlinked pieces of research which look both backwards and forwards (forwards near and far) at the prospects for moving towards diversified industrial cropping systems in the European context. To steer the investigation, I used a framework for conceptualizing this transition as a series of possible redefining steps for the arable field: from mono to strip to pixel. Combining systematic literature review, empirical studies, stakeholder interaction, and novel heuristic frameworks, I looked at the steps from multiple angles each starting from the same framing question: *does it work?* "It" is defined variably in the chapters as crop diversity research, strip cropping, pixel cropping, automation, and design, and I used multiple measures of success to assess what *it works!* could mean with a primary focus on the delivery of agroecosystem services (AES) (Chapters 3-5) and technology (Chapter 6). Synthesizing the findings of these various approaches, what do we learn about the prospects for a transition towards diversified industrial cropping systems? Do these steps work?

Via the literature review presented in Chapter 3, it became apparent how limited the scope of research has been to date around questions of AES delivery in legume-inclusive cropping systems, which comprise the largest share of the crop diversification niche in Europe (Hufnagel et al. 2020). In the reviewed body of literature, we saw that "works" is most often interpreted in productivist terms, despite indications from farmers that broader assessments are needed—likely a legacy of the post-WWII agricultural systems design regime which has favored certain crops and cultivation practices over others (Prost et al. 2017). If we take legume inclusion as a case and project the limitations of the productivist paradigm onto other diversification methods, the abundance of barriers becomes even greater, starting at the field and spanning the whole value chain (Antier et al. 2021; Morel et al. 2020). In particular, Chapter 3 highlighted the challenges to doing research on field- and farm-level measures of success that may transcend the boundaries of the experimental plot or study season, or of easily quantified and monetized AES. These are often the same measures that farmers have indicated they are interested in, for example pest and disease control (Pelzer et al. 2019), or those relevant to current societal debates, such as associated biodiversity (Leclère et al. 2020).

Taking the research gaps highlighted in Chapter 3 as inspiration for the empirical studies in Chapters 4 and 5, we zoomed in on some measures less well studied and assessed them in even less studied diversification systems. In Chapter 4 we assessed pest and disease control in strip cropping, and in Chapter 5 we looked at soil fertility, weed control, and associated biodiversity, as well as standard production indicators, in strip and pixel cropping. We developed a novel heuristic framework for classifying diversification practices on the farm and for quantifying the structural diversity of field practices and applied this framework to the analysis of AES delivery. In these chapters, we found that the answer to *does it work?* depended on the measures of success being targeted.

The recent global meta-analysis by Beillouin et al. (2021) concludes that some crop diversification strategies are more effective than others in supporting various AES, and we found that this held true in the Dutch context as well. Fig. 8.1 shows an aggregation of all the field data presented in Chapters 4 and 5, with AES indicator measures converted into *z*-scores[1] for comparability and then averaged at each treatment/resolution step. The contribution of individual AES measures and their performance for each treatment are shown in Fig. 8.1a. In Fig. 8.1b, indicators are grouped and averaged by AES category (each indicator given equal weight, although the amount of data support varies), and I have combined the multiple strip cropping treatments from the various studies to facilitate visualizing the data on the basis of the mono—strip—pixel scale. Aggregated in this way, overarching trends in the data become evident.

When looking at production measures, there is little change in the step between monoculture and strip cultivation but moving from strip to pixel tips productivity towards lower levels. Crop protection is improved marginally between monoculture and strip, but then also dips at pixel, a result of the selective hand-weeding practices employed in the pixel treatment. Looking more carefully at crop protection (Fig. 8.1a), we are reminded of the strong disease control effect of strip cropping found in Chapter 4. Soil fertility shows few changes between steps at the aggregated level. Biodiversity, on the other hand, continues to increase with each step with the higher natural enemy diversity observed in legume-added wheat strips in Chapter 4 and the higher weed species diversity found in the most diverse wheat treatments in Chapter 5.

Figure 8.1. (Facing page) Relationships between resolution of diversity and agroecosystem service (AES) delivery at the three steps of a transition towards diversification, according to the data presented in this thesis. Data from the empirical field studies presented in Chapters 4 and 5 (all years, all crops) are aggregated and converted into z-scores to allow for cross-indicator comparison. Points represent mean *z*-scores for each AES indicator/group at each diversity treatment/resolution; bars show standard error of the mean. Dotted lines between points are only for visualization purposes (making a visual link to Fig. 1.4 in Chapter 1) and do not indicate relationships between points as the x axis is not a continuous scale. Figure **a**: performance of individual AES indicators for each tested treatment. Figure **b**: AES indicators aggregated by indicator group and by diversity resolution step on the mono—strip—pixel pathway; STRIP is an aggregation of all strip treatments and AES groups are an aggregation of multiple indicators (see figure **a**) with all indicators weighted equally. Each indicator has different data support; see Materials & Methods sections of Chapters 4 and 5 for details.

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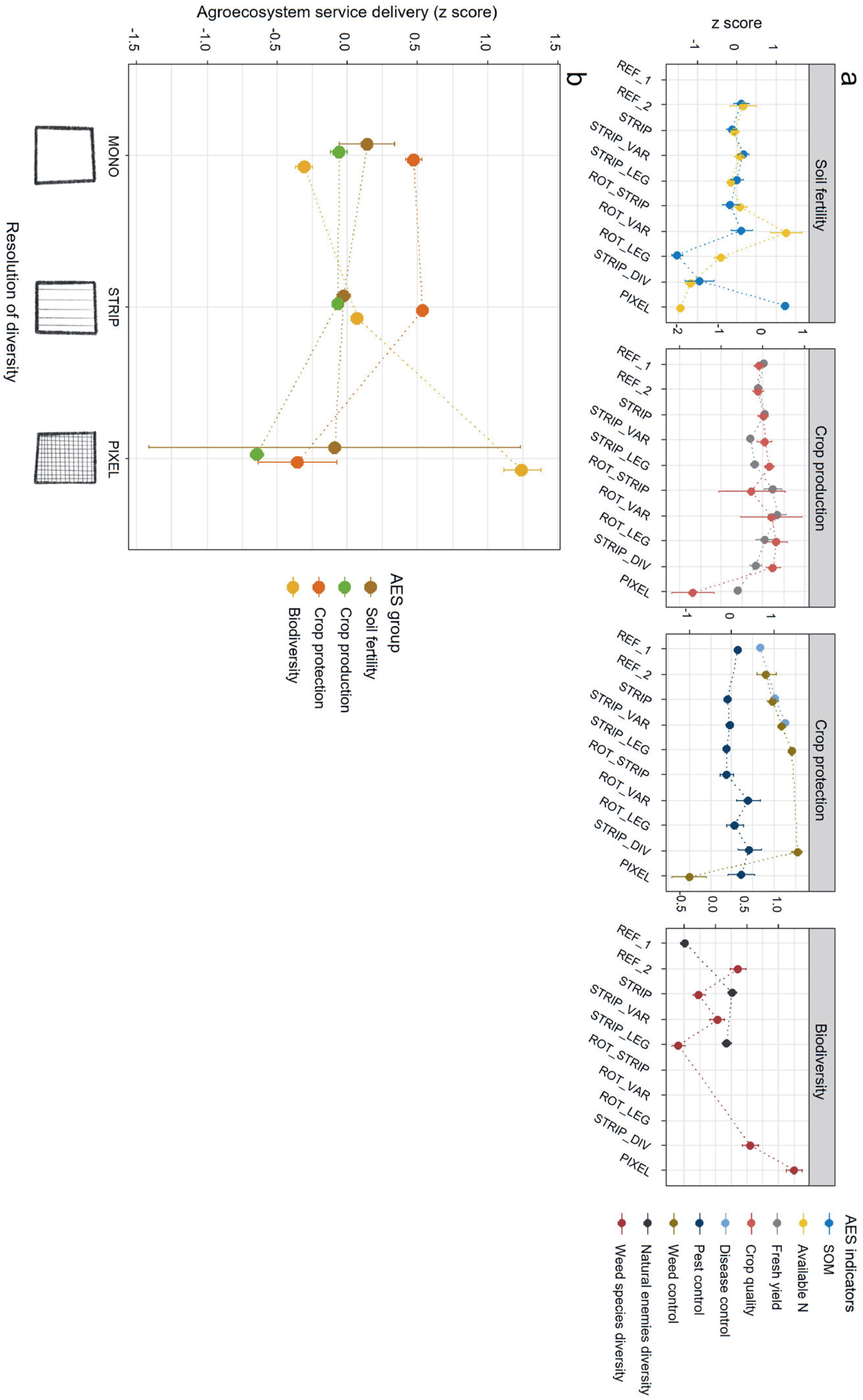
[1] $z = (x - \text{mean of the sample}) / \text{standard deviation of the sample}$


a
z score
Soil fertility
Crop production
Crop protection
Biodiversity
-1
0
1
-2
-0.5
0.0
0.5
1.0
REF_1
REF_2
STRIP
STRIP_VAR
STRIP_LEG
ROT_STRIP
ROT_VAR
ROT_LEG
STRIP_DIV
PIXEL
AES indicators
SOM
Available N
Fresh yield
Crop quality
Disease control
Pest control
Weed control
Natural enemies diversity
Weed species diversity
b
Agroecosystem service delivery (z score)
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
MONO
STRIP
PIXEL
Resolution of diversity
AES group
Soil fertility
Crop production
Crop protection
Biodiversity

8.1.2. How much diversity?

Here we arrive at an answer to the second framing question of this thesis, *how much crop diversity (how big a step) is needed to achieve both production and ecological goals?* The aggregated findings of the field studies strongly support the step to strip cropping both agronomically and ecologically in the Dutch organic context[2], indicating that production levels can be maintained while also gaining in crop protection and associated biodiversity. Taking the step from strip to pixel cropping, however, appears to result in a trade-off between production and biodiversity. What lies beyond (or adjacent to) pixel cropping is still unknown.

We were as yet unable to identify generalizable trends as to which diversity dimensions (time, space, or genes) were responsible for the AES delivery outcomes we observed in Chapter 5, in part because there was substantial variation in the AES responses within the strip step (between sole-cropped strips, legume-added strips, and mixed variety strips). However, there are clearer indications when looking at the data from both Chapters 4 and 5 together (Fig. 8.2). Here the trendlines suggest that higher scores for all three dimensions support better crop protection and biodiversity outcomes (primarily ecologically mediated services), while increasing spatial diversity has the strongest effect on bringing down production levels (both ecologically and management mediated services). I therefore suggest that until we can support these trends with more robust data support and analysis, the question of *how much crop diversity in needed?* should not be resolved on the basis of activating particular time—space—genes dimensions, but rather on the basis of balancing system-level effects, available resources, and desired outcomes. As long as this balance can be maintained according to the needs of the farmer and the local socio-ecological and innovation landscape they operate within[3], it appears that the more diversity (and no matter what kind: temporal, spatial, or genetic), the better for ecological outcomes.

The three-dimensional diversity heuristic (Chapter 4) and its extensions (Chapter 5) proved a powerful tool for visualizing and understanding the relationship between diversification practices, the cumulative effects of structural diversity, and AES delivery. With further improvements, this tool could be used to help farmers achieve a desirable balance between production and ecological outcomes and to direct policy support for doing so. Improvement would first rely on redesigning the field trials used to test the tool: in the experimental set-up utilized in Chapter 5, the diversity treatments contained more variation in some dimensions than others (Fig. 8.2). Supporting the three-dimensional diversity tool with more comprehensive data could involve designing a new field experiment in which diversity in each dimension is equally

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[2] A recent study in Germany suggests that the ecological gains of strip cropping can also apply in conventional systems: both biodiversity and biological pest control were enhanced in wheat—oilseed rape strip intercrops compared to monocultural references (Alarcón-Segura et al. 2022).

[3] Policy has a large role to play in shaping these landscapes: a recent study in the USA found that favorable regional policy was a key predictor in determining whether farmers used simplified or diversified crop rotations (Socolar et al. 2021).

and substantially varied, however doing so would require a very complicated, large, and long-term experimental set-up.

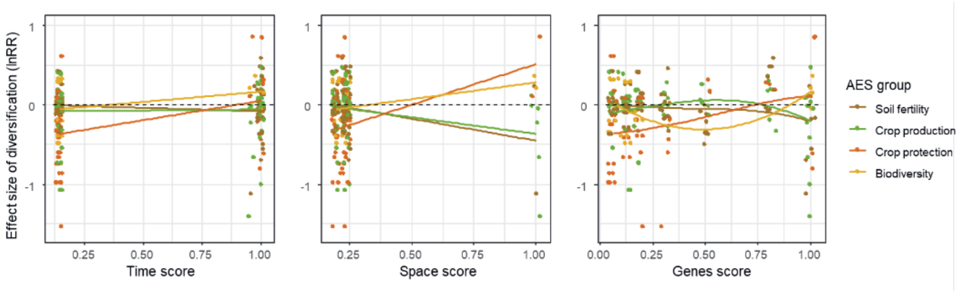

Figure 8.2. Relationships between diversity dimension scores and agroecosystem service (AES) delivery as indicated by the data presented in this thesis. All data from the empirical field studies presented in Chapters 4 and 5 (all years, all crops) are included in the plots. Points show the effect size of the diversification method relative to the monocultural reference, calculated as the log response ratio (lnRR). Trend lines show smoothed conditional means (in the time and space plots lines are generated using the "lm" method in R, in the genes plot lines are generated using the "loess" method). Horizontal dotted lines show the point at which the effect of diversification is equal to the monoculture reference. Data for individual AES indicators are coded by AES group (see Fig. 8.1a for an explanation of which indicators are included in each category).

In Chapter 5 we hypothesized that the trade-off between production and ecological aims at high-resolution in-field diversity is the result of management puzzles not yet solved, and of the complexity of ecological relations and interactions emerging in a pixel cropping layout compared to a mono- or strip-cropped field. In the pixel field, complex networks of ecological relations and interactions appear to strongly support associated biodiversity—that is, the arrival of a greater variety of epigeic arthropods and arable flora—which is then invited to stay within the system through either deliberate or implicit (in)action (Fig. 8.3a). If biodiversity is the sole aim, then a move towards resolutions of diversity higher than strip cropping could be warranted. However, pixel cropping is devised as an agricultural system—the core aim of which remains production—and in this regard the emergent complexity does not seem to support crop production well enough for the tested crops under the tested management regimen and when assessed against the same yardstick as the higher-input and machine-managed monocultural reference (Fig. 8.3b). Answering the third framing question of this thesis then comes center stage as imperative for reconciling the trade-off between production and biodiversity at high resolutions of planned in-field heterogeneity: *what does cultivating this much diversity mean for management and technology?* A first stop in finding an answer is to acknowledge that while strip cropping for the most part "works" from a management and technology perspective, pixel cropping does not (yet), and here we run into the issues explored in Chapter 6.

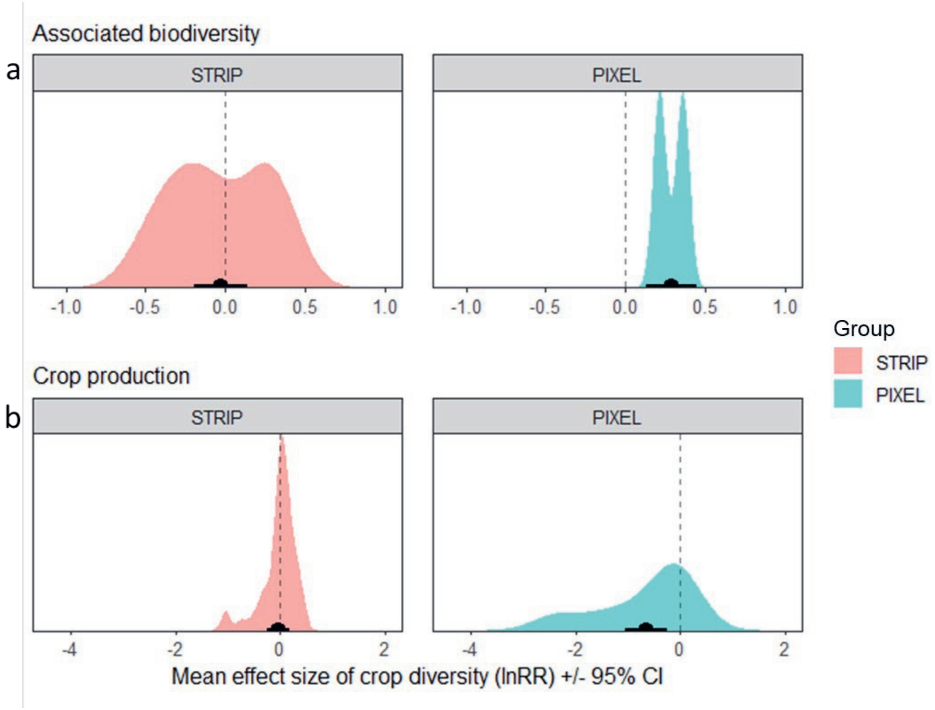

Figure 8.3. Impact of crop diversification steps on associated biodiversity (**a**) and production (**b**). Shaded areas show the distribution of the field data analyzed in Chapters 4 and 5. Indicator measures have been aggregated into the categories ‘crop production’ (includes data for fresh yield and crop quality measures) and ‘associated biodiversity’ (includes data for natural enemy species richness and diversity and weed species richness and diversity). Points represent the mean effect size (log response ratio, lnRR) of the diversification treatment group relative to the monoculture reference. Lines show the 95% confidence interval (CI), i.e. the range of values that likely contains the mean of the data displayed. Vertical dotted lines show the point at which the effect of diversification is equal to the monoculture reference.

8.1.3. Management and technology

In the General Introduction of this thesis, I presented the mono—strip—pixel transition as a series of three consecutive steps in a transition pathway. My research has shown, however, that there is a technological barrier preventing progress between strip and pixel. The field data analyzed in Chapter 5 point to the management tipping point that currently exists between strip (where tractors can still operate) and pixel (where no standard farm machinery can yet operate), highlighting that moving from strip to pixel is much bigger leap than moving from mono to strip. Chapter 6 then shows that technological advances being pushed into arable agriculture do not currently support the leap from strip to pixel. On the contrary, mechanization and automation pathways being promoted under the banner of sustainability most often lead back to monocultural production systems, effectively bolstering the lock-ins that maintain monocultures as the dominant production mode in Europe. Technological development is not progressing a transition towards more diverse cropping systems in industrialized contexts, but rather cyclically reinforcing monocultural production modes with increasingly more precise techno-fixes (Fig. 8.4).

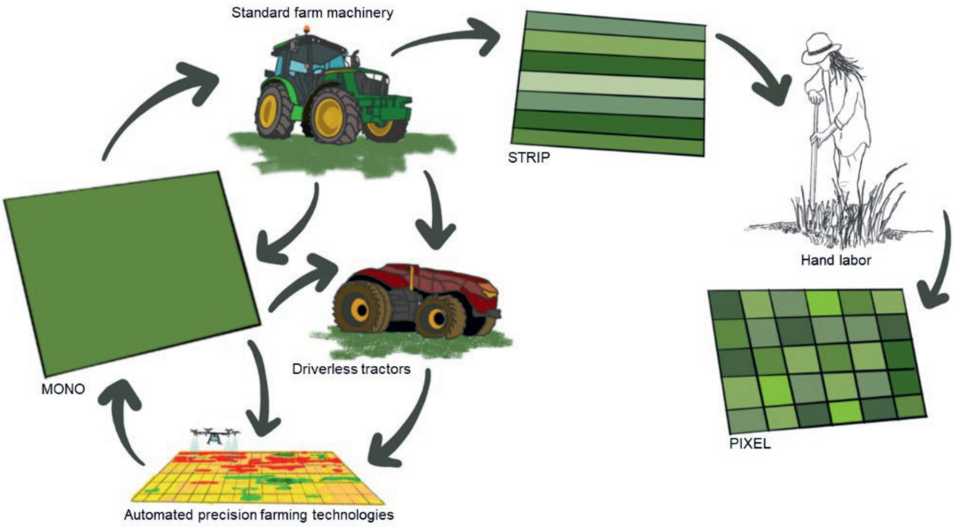

Figure 8.4. An expanded version of the mono—strip—pixel transition presented in the Introduction (Fig. 1.3), bringing in the role of technology in facilitating the transition. Currently, the only way to step from strip to pixel is to cultivate the field by hand.

Strip cropping offers one way out of the cycle: it can be implemented with monocultural tools and is therefore currently accessible to farmers willing to take on the cognitive challenge of using those tools to redefine their fields (Juventia et al. 2022), although some mechanical shortcomings[4] still need to be solved (van der Voort et al. 2021). Moving beyond strip cropping—and farther into the three-dimensional diversity space—means that standard farm machinery no longer applies. A farmer aspiring to practice pixel cropping in an industrial setting now runs into a technological dead end—the tools to make it work at scale do not yet exist, so the only option is to do the work by hand. A main conclusion of Chapter 6 was that monocultural thinking only reinforces this dead end, and therefore should not be the starting point for design processes aiming to generate appropriate tools for polycultural, agroecological farming systems. Here we found that getting highly diverse cropping systems to work practically likely means embracing new tools and arrangements to do the daily labor, as well as inviting more diversity—both in participants and in methodologies—into the tool design process.

Moving away from monocultural thinking also probably requires rethinking how agricultural research projects seeking to foster transformative change are themselves designed, implemented,

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[4] Remaining mechanical challenges to using standard farm machinery in strip cropping mostly relate to cultivation activities which need to be targeted to a single crop and not the neighbouring strip, e.g. irrigation, fertilization, some harvesting activities, and spraying crop protection products in conventional systems.

and evaluated. I use this premise as a springboard for discussing the broader implications of the research, braiding in wider perspectives on agronomy, ecology, science and technology, design, and transitions in agriculture.

8.2. Diversified industrial cropping systems?

> *If you are in a shipwreck and all the boats are gone, a piano top buoyant enough to keep you afloat that comes along makes a fortuitous life preserver. But this is not to say that the best way to design a life preserver is in the form of a piano top.*
>
> Buckminster Fuller (1969)

In the General Introduction, I highlighted the polarized debates that dominate societal imaginaries about the future of agriculture and argued for a need to populate the middle ground, asking whether diversification and intensive production are compatible and how we might design and evaluate cropping systems that qualify as both industrial and agroecological. The research presented in this thesis offers a starting point for answering these questions in the Dutch context. Chapters 4 and 5 make a strong case for strip cropping to improve ecological aims without incurring yield penalties in the Netherlands, especially as an approach for mitigating potato late blight disease in organic farming systems. They also point to the positive effects of crop diversification in general on associated agrobiodiversity in intensive production systems, a highly relevant finding in light of the current dialogue on bending the curve of biodiversity loss (Leclère et al. 2020; Mace et al. 2018). These findings suggest that there is indeed room for combining agroecological and industrial practices—a conclusion that will likely gain in relevance as the European Commission's goals for sustainable food production come under fire as a result of the Russian attack on Ukraine.

Taking a step back from the situated context of the field experiment results and weaving in the past and future lessons of Chapters 3 and 6, however, reveals a tension embedded within mono—strip—pixel pathway framing this thesis that could weaken the premise of achieving diversified industrial cropping systems via this route. The mono—strip—pixel framework positions strip and pixel cropping as part of a linear progression that originates in monocultural systems. Does this framing inherently lock out pathways and solutions not rooted in monocultural thinking? While dually upholding the value of the research's empirical contributions, I propose that reflecting on the conceptual assumptions underlying the fundamental premise of the research also offers a valuable contribution to the agricultural transitions dialogue. Unravelling the possible implications of the mono—strip—pixel framing requires first delving into the origins of what I label in Chapter 6 the 'monoculture mindset' and then unpacking the ways such a mindset may be embedded into cropping systems research and design frameworks, including the three-step transition employed here.

8.2.1. The monoculture mindset

We can trace the philosophical origins of the monoculture mindset to interconnected narratives that together map a historical shift in Western culture away from revering nature and towards a view based on separation. These narratives include the rise of patriarchal religion, the scientific revolution, and the domination of colonial, imperial, and capitalist programs. With the advent of patriarchal religion, a hierarchical chain of being was established which placed 'man' (i.e. cisgendered men) at the top, and other genders, non-humans, and nature at the bottom, justifying what ecofeminists have termed a "logic of domination" (Warren 1990). The separation of humans from nature was codified by the works of figures such as Francis Bacon and René Descartes, who during the 1600s taught Western society to understand nature as inert and as a machine which would be understood through reason and reductionism (Gerber and Hiernaux 2022; Merchant 2006). The combined power of value dualisms (e.g. self vs. other) and mechanistic thinking were put to work in colonial and imperial projects in the development of the fields of botany and plant breeding, and the replacement of indigenous farming practices with plantations on occupied lands (Davis et al. 2019; Katsof 2021). Braiding these threads together leads us to the monocultural approach to crop production, which positions plants as machines, considers agriculture separate from nature, emphasizes input—output efficiency, and demands homogeneity, all characteristics supported by a particular (i.e. Western) way of conceiving and generating scientific knowledge (Haraway 2016; Montenegro de Wit 2021; Shiva 1993; Tittonell 2014). The peak of monoculture thinking is exemplified by the Green Revolution, which spread its dualisms, value hierarchies, and logic of domination across what are now the industrial farming landscapes that I have problematized in the General Introduction of this thesis.

Utilizing the three-step mono—strip—pixel framework has been useful for illuminating the prospects and challenges facing diversification in industrial agriculture, offering insight into possible AES trade-offs and tipping points between steps. However, it also makes assumptions that are based on knowledge produced with a monoculture mindset. Cutting a monocultural field into smaller, orthogonal subsections (strips, pixels) is a very 'Cartesian' way of conceiving a transition towards diversified farming systems (Driessen 2020), and produces a particular kind of scientific knowledge for a particular audience. This is especially evident in pixel cropping, where in seeking to mimic nature while also making the system fit within the bounds of the scientific method, design choices had to be made that probably limit the prospects of the system. The method plays with complexity, but within a reductionist framework. For example, we randomized the location of each crop in the pixel layout in a kind of *tabula rasa* approach to agronomic experimentation even while knowing that indigenous knowledge about effective companion planting guilds already exists (e.g. Rodríguez-Robayo et al. 2020; Slotten et al. 2020).

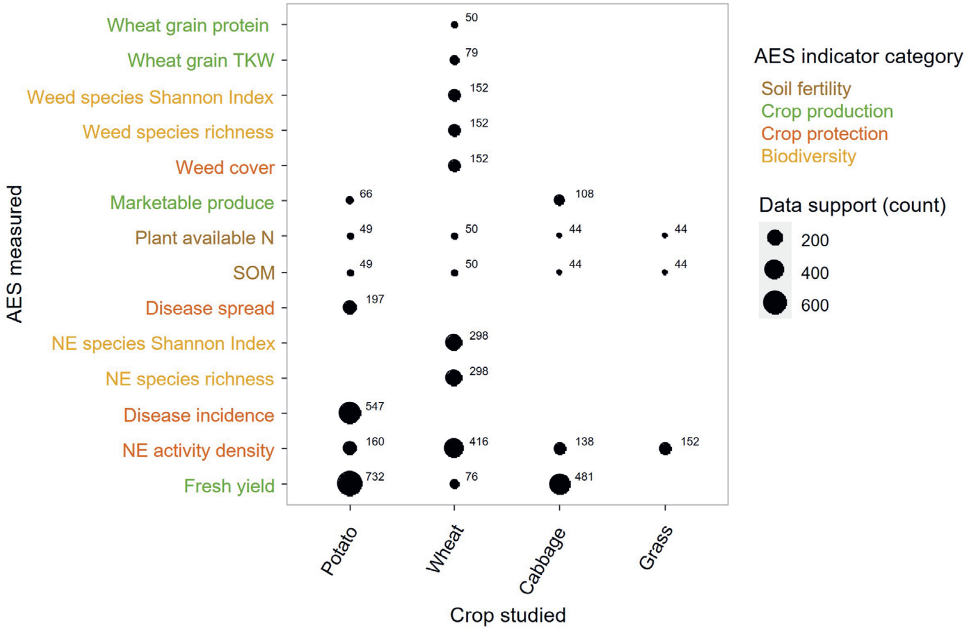

Figure 8.5. Matrix showing the number of individual data points collected (support) in the field research presented in Chapters 4 and 5 for each agroecosystem service (AES) indicator monitored. The larger the symbol, the more data support (exact counts are given next to each symbol).

The concept of ecosystems services which I have used to assess the performance of each step can also be critiqued in this light. Understanding the processes of nature as the production of goods and services for the benefit of humans positions plants in an agroecosystem (and any other system inhabitants, such as soil microorganisms, earth worms, arthropods, birds, etc.) as being in service to human wellbeing and economy (Costanza et al. 1997; Gerber and Hiernaux 2022). In this way, the notions of 'success' used in this research (agroecosystem services) also maintain a fundamental link to the monoculture mindset, although they go beyond the standard productivist terms most commonly utilized (Chapter 3). Comparing the indicators of success used in the field studies presented in Chapters 4 and 5 to what we found for legume research in Chapter 3 shows a shift in research focus (Fig. 8.5), however there are still plenty of empty spaces in the matrix that could be filled even within the AES approach: due to both demand and current knowledge on how to measure AES, yield remained the main focus of our measurements.

A move away from monocultural agriculture implies shedding—or at the least becoming aware of—an abundance of problematic baggage which accompanies any transition pathway that carries over tropes of monocultural thinking. The question is how to do this shedding. Scholars in the agricultural systems design literature have advocated for various frameworks which conceive the transition as a series of progressive steps as I have done in this thesis (e.g. Hill and MacRae 1996), and have called for reflexivity in design processes as a way to question underlying assumptions and make room for novel approaches (Bos et al. 2013; Meynard et al. 2012). An alternative would be to not carry over tropes of monocultural thinking into design processes in the first place. How should we then think about a design process for diversifying industrial agriculture that starts somewhere other than monoculture? Would it lead to increasingly smaller pixels, or to something else?

8.2.2. Designing non-monocultures

In the agricultural systems sciences, design thinking and design methodologies are frequently employed towards the aims of re-designing farming system towards greater sustainability, but they tend to come from a positionality that is rooted in a particular design agenda. Prost et al. (2017) offer an excellent summary of the post-WWII agricultural design agenda which led to the widespread specialization of European farming systems, homogenization of farm fields, and pervasive dependence on agricultural inputs. Many farming systems re-design methodologies could be seen as efforts to make this agenda now produce different, more sustainable outcomes.

Following Prost et al. (2017), we can think of diversified industrial cropping systems as a design object, or as the interplay between multiple design objects (e.g. plant breeds, crop rotations, machines, etc.). Design processes which start with the status quo and seek to make (incremental) alterations to the cropping system will always maintain ties to the origin system: as Donna Haraway reminds us, “it matters which stories tell stories, which concepts think concepts” (2016, p. 101). One way to circumvent the monoculture mindset seems to be to invite people not involved in agriculture to engage in creative design processes (Chapter 6). Other alternatives applicable to agroecological systems which might provide an antidote to monocultural thinking include permaculture design processes (Ferguson and Lovell 2014), visioning (Francis et al. 2017), think-do gap analysis (O’Sullivan et al. 2018), and speculative design (Dunne and Raby 2013), each of which asks first where we want to be in the future and then works backwards towards understanding how to get there without necessarily carrying forward the baggage of the present system’s assumptions. The mono—strip—pixel framework, on the other hand, adheres to a ‘step-by-step’ design process (Meynard et al. 2012), and thereby maintains close alliances with the dominant conceptual (and also aesthetic) regime tied to ‘good’ farming (Burton 2004).

I have argued elsewhere in this thesis, following a strong precedent in the agricultural systems design literature (Duru et al. 2015a; Meynard et al. 2012), that stair-steps offer farmers an accessible pathway towards more fundamental reorganization of cropping systems for meeting societal demands, and I maintain that strip cropping serves this valuable role as a design for the present and near future. Strip cropping is in fact not necessarily a *new* step: strip cropping has been practiced for a long time in other parts of the world, namely China (Hong et al. 2017) and formerly in the United States (Fig. 8.6, left) (Francis et al. 1986). Strip-like cropping also sometimes occurs by default due to historical land ownership and partitioning practices (Fig. 8.6, right). As the Dutch Farm of the Future imagines it, the future is “closer than you think;” if strip cropping is the future, then the future is (can be) here now.

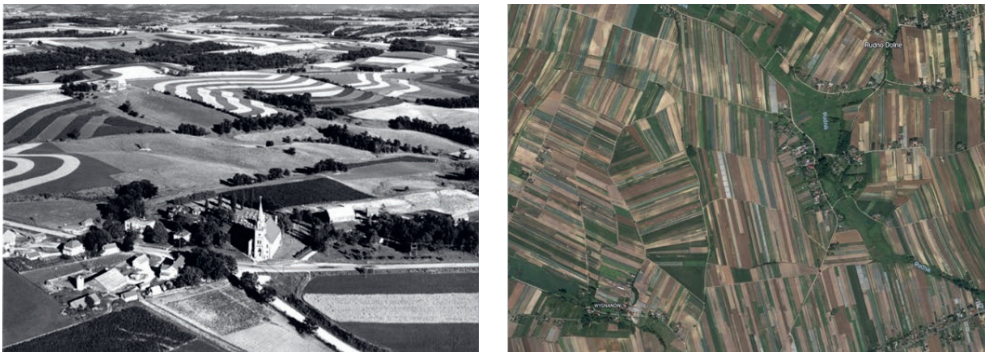

Figure 8.6. A different aesthetic for farming landscapes: strip cropping in the past as a form of erosion control and fertilizer reduction (1950s Wisconsin, USA, **left**) and by 'default' in the present (north-east of Kraków, Poland, **right**). Image credits: left: E. W. Cole, USDA, July 1957; right: Google Earth, 50°07'34"N 20°17'55"E, accessed 11/05/2022.

In the *Countryside* exhibition described in Chapter 7, we presented pixel cropping as a "radical redesign" of industrial arable cropping (Ditzler 2020). Considering the present discussion, pixel cropping's claim to radicalness is less robust. I have often found myself describing pixel cropping as a production system that is designed "to look and act like a natural ecosystem," but can that be true within the confines of a Cartesian grid? Scholars studying farming innovations and indigenous design practices posit that design is ontological, the designed artifacts bringing about particular ways of being, knowing, and doing (Escobar 2018; Legun and Burch 2021). Pixel cropping is inspired by practices that originated outside of Cartesian dualism (e.g. the Three Sisters or *milpa*, Lopez-Ridaura et al. (2021)), but it then forces those practices into the (literal) box of row-based farming, albeit a very short and narrow row. As a result, the intimate ecological mingling that makes the Three Sisters work so well in production terms is probably negated in a pixelated layout and with crops chosen to reflect standard Dutch monocultural practices rather than for their ecological affinity. We could thus conclude that pixel cropping—as it is currently conceived and with its origins in monoculture thinking—is unlikely to precipitate a truly new way of designing farming systems, nor a perfect translation of traditional agroecological practices into industrial terms.

8.2.3. Cultivating complexity

If we let go of linear thinking, not just mono—strip—pixel but also the straight lines that define the field management unit, we might arrive at a differently arranged, messier, more collaborative assemblage (Tsing 2015), with a new aesthetic, that better supports the ambition to "act like nature" while also producing food for humans. This would mean adopting design and experimentation processes oriented towards generating and managing complexity, rather than towards incrementally increasing diversity. Here it is important to distinguish the difference between diversity and complexity.

In this thesis, 'diversification' is used to describe the introduction of planned heterogeneity into the (previously monocultural) arable field. Being an agricultural system, this heterogeneity is designed, and designed to be managed. Complexity, on the other hand, I would define as the web of relations that emerge from (planned) heterogeneity (Paoli et al. 2016; Vandermeer and Perfecto 2017); in the case of the arable field, these include relations between humans, non-humans, ecological processes, and farming tools at multiple hierarchical scales. Designing *for* complexity then becomes something different than inserting heterogeneity into a control-based cropping system and may not be compatible with industrial aims, although there are calls to reconcile these differences (Tittonell et al. 2020). Further, the potential for experimentation exponentially grows as when seeking to generate complexity the possibilities for combinations of crops, layouts, rotations, treatments, etc. radically multiply. These possibilities probably require a different approach to agronomic experimentation (perhaps greater interplay between plant modelling techniques and in-field trials), as well as different roles for farmers and farm workers, and the generation of a diversity of forms of knowledge that guide farming practices. In addition to addressing the management tipping point between strip and pixel, we must also address the knowledge tipping point between industrial agriculture as it is practiced today and (new) kinds of farming designed for complexity.

Some agricultural systems scientists have used the concept of complex adaptive systems as a way to understand the design requirements of diversified agroecosystems (Duru et al. 2015a). I would argue that a step further is needed, one which centers the valorization and creation of knowledge forms not usually recognized in Western science nor in monocultural thinking: indigenous knowledge (Boillat and Berkes 2013), farmers' and farm workers' embodied knowledge (Carolan 2008; Krzywoszynska 2016), more-than-human knowledge (van Dooren et al. 2016), and knowledge 'from below' (Middelveld et al. 2021). Design dialogues around the technologies made to support complex systems would also need to shift, away from naming, classifying, and sensing everything and instead towards generating the kinds of relations that lead to the desired outcomes (Chapter 6). These changes would imply embracing a complexity aesthetic, which would involve a deep cultural shift in how farms and farming landscapes are seen and valued (Junge et al. 2015). We explored this in the way we displayed pixel cropping in the *Countryside* exhibition (Chapter 7), where we highlighted the contrast between the ordered view of the pixel field map from above with the riotously diverse reality of the actual field when viewed from plant level. Farm aesthetics—and particularly those tied to conventional measures of production such as orderly fields and uniform crop stands—are important in the formation of many farmers' identities; in a post-productivist and complexity-centric design paradigm, farmers might instead identify themselves (and be judged by others) by measures such as the number of bird species found on their land or the presence of rare weeds (Burton 2004).

8.3. Towards process-relational thinking in agricultural systems research

Adopting the kinds of design processes that may better foster a move away from monoculture thinking and towards embracing complexity in industrial agricultural systems implies not only the consequences I briefly surveyed in the previous section, but also a reframing of how cropping systems are understood to be successful (*it works!*) in meeting the multifaceted demands of society. I argue here that pulling a new conceptual thread into the braid—a *process-relational* perspective—offers a way to rethink how we measure success in diversified cropping systems, with implications for how agroecological research is conducted.

8.3.1. Redefining success

When it comes to implementing a novel design idea, practical challenges arise—not just in terms of management, but also in terms of research. As highlighted in Chapters 3, 4, and 5, studying diversity requires working at appropriate temporal and spatial scales, which tend to be broader than most research stations and funding schemes can easily accommodate. An approach like that taken in the DiverIMPACTS and LegValue projects—to connect a diversity of field experiments operating at different scales in a multi-site network—can be valuable in overcoming these constraints. However, it also presents difficulties in interpreting experimental results (*does it work?*). A DiverIMPACTS report presenting a multi-site analysis of the multiple diversification practices employed at all the project's field experiments concluded that broadly applicable conclusions about the effectiveness of crop diversity are not (yet) attainable. As we encountered in Chapters 4 and 5, crop diversity in the field begets diversity in the data which makes it difficult to quantify the benefits of a diversified system relative to a monoculture. Further, local conditions precipitate different outcomes. Rather than define generalized recommendations, the DiverIMPACTS report instead distills a list of 'ingredients' for successful crop diversification which can be combined into various recipes adapted to local conditions, constraints, and objectives (Hellou and Chongtham Iman 2022). These include transitioning incrementally, combining practices, utilizing service crops in addition to harvestable crops, and taking a whole system (rather than substitution) approach. The final ingredient is adopting adaptive management: acknowledging that crop diversification pathways are dynamic, that conditions change from season to season, and that biotic, climatic, and socio-economic shifts often arise unexpectedly (Hellou and Chongtham Iman 2022).

The ingredients approach, with an emphasis on adaptive management, implies that individual and local learning must come before generalizable learning in the transition to diversified arable agriculture. The reality of a four-year research project, however, makes it challenging to embrace dynamic change in the field, particularly in the context of a research grant and PhD project which expect concrete outputs, e.g. peer-reviewed published articles or policy recommendations based on statistically significant findings in which the benefits of diversified systems are quantified relative to the yardstick of a monocultural reference. How should we then deal with 'anomalies' typical to systems experiments, such as variation in the data, climate variations, management errors, changes to the experimental design, or interference by wildlife?

In her article calling for sociological approaches that capture the complexity and dynamism of farming, Ika Darnhofer (2020) proposes that adopting a process-relational perspective is a viable antidote to the reductionist, dualist, anthropocentric, and essentialist ontological roots which I have argued are the pillars of monoculture thinking. To summarize Darnhofer's key points, a process-relational perspective reconceptualizes the farm as an evolving and dynamic, lively and affective, assemblage of processes and relations that are interdependent with their environment (Darnhofer 2020, p. 513-515). Central to understanding the act of farming from this perspective is to acknowledge that complexity leads to unpredictable effects and unintended consequences. Rather than see these effects as problematic or prohibitive, Darnhofer argues we should see them as generative—creating openings that can "enlarge what is perceived as 'possible' and 'doable'" on the farm (Darnhofer 2020, p. 512).

We can use the process-relational perspective to understand the transition away from monocultures not as a series of steps that move towards smaller and smaller orthogonal field units, but rather as a process of inviting and incorporating wider webs of relations—between plants, arthropods, soil organisms, farmers, tools, etc.—into the conception of the cropping system. What would that mean for researchers seeking to measure indicators of performance in novel diversified cropping systems experiments? Taking soil quality as an example, we can quickly see the shortcomings of performance indicators like those employed in this thesis when they are assessed as stand-alone measures of success.

8.3.2. Process-relational agronomy?

In Chapter 5 I utilized two very basic indicators of soil fertility: plant-available nitrogen and soil organic matter content. A first problem, from a process-relational perspective, is that both indicators are the result of processes happening on multiple time scales and yet are measured and assessed equally at one fixed point in time. Second, these indicators are positioned to assess success from the perspective of the crop plant and by extension the human harvesting the crop plant, not taking into account affective relations with non-crop organisms and processes (e.g., *what's in it for the earth worms?*). Expanding the measure of soil fertility from a process-relational perspective could help agricultural systems scientists move beyond the productionist ethos (i.e. the monoculture yardstick) (Puig de la Bellacasa 2019) and towards a collaborative view (Meulemans 2020). Rather than measuring two static indicators, this might include asking a web of interlinking questions such as: what kinds of root architecture does this level of soil fertility precipitate in the crop?; how do roots in this environment interact (differently) with neighboring plants?; what do these interactions mean for mycorrhizal networks or soil fauna?; (how) does the presence/absence of those soil fauna impact local beetle and bird communities?; what impact do these organisms have on pest management?; do the birds and beetles bring the farmer joy?; what kind of knowledge does a farmer need to cultivate these relations?; and so on. Each of these questions are indeed being asked by scientists, but by different scientists working in different disciplines. When you add the other AES category measures I have used in this thesis into the equation, we see that *'process-relational agronomy'* or *'process-relational agroecology'* (taking agroecology here to mean the science per Wezel et al. (2009)) quickly becomes a transdisciplinary challenge, moving beyond what can be captured even by complex ecological theory (Vandermeer and Perfecto 2017) or functional approaches (Schulte et al. 2019).

Although certainly complicated, adopting a process-relational perspective in agricultural systems research offers a key advantage over the dominant static indicator approach. Returning to the notion of seeing farming as a dynamic and evolving series of openings for change, accepting that farming is a "response to expected as well as unexpected phenomena" (Darnhofer 2020, p. 515) and building that into measures of success allows room for 'anomalies' and 'outliers' (e.g. climate variations, management errors, changes to the experimental design, or interference by wildlife) to be seen instead as a central part of the process. In Chapter 5 we struggled to find statistical differences between the behavior of the diversity treatments at the Wageningen field experiment, in what could be seen as a shortcoming of field research on a short timeframe and of static performance measures assessed at the plot and field level, despite the field experiment having been designed in reference to decades of cropping systems research. What this analysis did not account for was the learning that took place in the field over the years as drought, fertilization mistakes, changes to the crop rotation, and birds eating all the grain in our pixel plots offered the research and farmer team opportunities to adjust and adapt our understanding and management of the system[5]. Such learning may in fact be responsible for increasing production indicators: a study looking at farmers transitioning from conventional to organic production in the USA hypothesized that an observed reduction in yield gaps over time was due in large part to farmers' experiential learning (Martini et al. 2004). When in-the-field learning is paired with the kind of collaborative design work done with a wide range of people as in Chapters 6 and 7, we gain an expanded view of what works in and for the tested cropping systems by looking beyond the standard agronomic methods and static measures to envision the many other dynamic aspects and impacts of the systems.

As we saw in Chapter 3, taking a systems view in a farming context is necessary for moving beyond productivist measures of success, but it also implies incorporating system evolution into methodological approaches. Learning and adaptation are key to understanding and managing farming systems transitions and should be embedded in systems experiments (Drinkwater 2002; Mawois et al. 2019). Metrics which seek to capture system complexity (e.g. Paoli et al. 2016; Steinfeld et al. in preparation), rather than system heterogeneity as we proposed in Chapter 5, might be better suited to capturing the processes and relations at play when assessing response relationships between these metrics and system performance indicators. "It works" then also has

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[5] As it happens, the birds that ate all the grain in our pixel plots one summer were likely a breeding pair of Grey Partridges (*patrijzen* in Dutch), a red list protected species. In this new frame of thinking, the grain being eaten could be seen as a success of the system (beneficial for biodiversity) rather than a failure (detrimental for yields).

to be seen as a dynamic assessment, much in the same way resilience has been more recently conceptualized (Darnhofer 2021a); in this approach, the focus is shifted from static indicators to the identification of tipping points and capacities to facilitate transformations. How to incorporate these qualities into the three-dimensional diversity heuristic and extensions presented in Chapters 4 and 5 remains an open question, although approaches such as those employed in resilience and vulnerability assessments could provide a starting point (see e.g. Luers 2005).

8.4. New imaginations for the future of farming

To tie off the braid, I would like to come back to where I began the General Introduction: with a historical anecdote that may help us to understand—and then rethink—imaginations for near and far farming futures.

In 1968, having been inspired by Buckminster Fuller's proposition that 'flat-earth thinking' was at the root of all societal and environmental problems, the young biologist—activist Stewart Brand marched the streets of San Francisco wearing a sandwich board demanding an answer: "Why haven't we seen a photograph of the whole Earth yet?" Just a few months later, NASA would release that photograph, the first full-color digital image mosaic of planet Earth from space, captured by the ATS-3 satellite. The 'whole Earth' image was soon featured on the cover of the debut issue of Brand's *Whole Earth Catalog*, a periodical with the ambition to carve out societal space for new thinking about ecology and technology. The catalog's motto was "access to tools." The tools on offer ranged from seeds to books to plumbing equipment to plans for building your own geodesic dome, as well as essays, musings, and propositions by environmentalists, ecologists, software engineers, architects, and other voices of the counterculture movement. Access to tools meant access to different ways of knowing and being and to practical approaches for imagining and constructing a future—both personal and collective—using whole-Earth thinking. The *Whole Earth Catalog* is an icon of its time, and is credited with steering decades of environmentalism in its wake (Kirk 2007).

We have now become accustomed to seeing images of the whole Earth and beyond, but the urgency for whole-Earth thinking has only amplified. The kinds of tools this thesis explores are in some ways quite different from what was relevant in 1968. But questions about self-sufficiency, sustainability, ecology, technology, and down-to-earth problem solving have only gained in relevance since the *Catalog*'s debut. Its legacy inspires us to ask questions like those embedded in this thesis: Where have we come from in our thinking about the productivity, sustainability, and design of industrial cropping systems? Where do we want to be in the future? And what tools do we need to get there?

The *Whole Earth Catalog* had a fairly brief run as Brand and his cohort of eco-technical thinkers moved on to other projects. Among those was a collaboration with computer scientist Danny Hillis, which they called The Clock of the Long Now. The idea was simple: devise a way of recording time that could surpass the 'Year 10,000 Problem' and outlive our imagination of the 'foreseeable' future (Brand 2008). The clock itself (still under construction) was designed as a physical object capable of self-regulating for 10,000 years and has questionable prospects at functionality. But like whole-Earth thinking, the idea of the Long Now is highly functional and necessary, calling for a recalibration in how we think about the future and on what timeline. The Clock of the Long Now asks us to extend our notion of the future not only beyond the impact of our own lifetimes but vastly further afield, and with it to extend our sense of responsibility (and response-ability) towards the planet and thereby reconsider the ecomodernist tendency to prioritize the short-term fix.

8.4.1. Iconic imaginaries

Throughout the history of science, the power of icons—striking and recognizable visuals or narratives—is a key feature in stories of groundbreaking discovery and collective paradigm shifts (Westley and Folke 2018). Like the *Whole Earth Catalog* and the Clock of the Long Now, NASA's later *Blue Marble* (1972) photograph and Rachel Carson's book Silent Spring (1962) (both appearing around the time that the monoculture mindset was being codified via the Green Revolution) are examples of icons that captured the public imagination, catalyzing radical changes in the way people thought about ecological connectedness, environmental stewardship, human impact on the planet, and the need for a transformation towards a more sustainable relationship with Earth. The *National Geographic*'s 1970 illustration (Chapter 1, Fig. 1.1) and the Dutch Farm of the Future are both iterations of the same notion—the idea of a singular 'farm of the future'—and both draw on the power of icons. We can think about the transformative power of icons as coming from their capacity to attract, connect, and provoke (Westley and Folke 2018). By this definition, I would argue that a primary value of the mono—strip—pixel transition framework lies not seeing it as a series of actual practices that should be implemented in place of monocultures, but in seeing it as an icon with the transformative power to extend imaginations beyond monocultural futures.

Figure 8.7. Iconic Dutch farming systems: aerial view of a strip-cropped field at ERF B.V. near Almere, NL (**left**), and a close-up view of a pixel plot at the Wageningen University pixel cropping field trial in Wageningen, NL (**right**). Image credits: left: ERF B.V., 2018; right: Peter van der Zee / Unifarm, 2021.

Both strip and pixel cropping are visually striking (Fig. 8.7). Strip cropping looks stunning mid-season, and we have seen and heard from farmers that iconic visuals of strip-cropped fields play an important role in attracting public attention and in showing other farmers—physically and at viable scales—that change is possible (Akkerwijzer 2020). Visuals such as these have been shown to play an important role in the implementation of radical agricultural system changes, serving as boundary objects which connect different types of actors in innovation processes (Klerkx et al. 2012). Pixel cropping seems to have even more iconic power—a key reason it got us into the *Countryside* exhibition in the first place.

During my thesis research I spent a lot of time hosting visitors at the strip and pixel cropping field experiment in Wageningen: student groups, architects, robotics developers, designers, international delegations, the President of Wageningen University, the Director General of Agriculture and Rural Development for the European Commission, colleagues, and friends. Every time, without fail, the pixel cropping plots stole the show from strip cropping. I had many opportunities to try to explain what pixel cropping was, why we were testing it, the logic of its design, the statistical outcomes, and the management challenges, and over time I found myself shifting in my understanding of the value of the system. When I first laid out the pixel plots in the spring of 2018, I was convinced of the logic: the future of industrial arable farming will look like pixel cropping. As my fieldwork drew to a close I was no longer convinced, in part because the experience of standing in the pixel field and talking about it with so many different people made me realize that the core value of the trial, superseding its potential to serve as a proof of principle or as a statistically comparable experimental treatment (i.e. a practical step in the conceptual mono—strip—pixel transition), was its capacity to open up a dialogue around speculative design for the future of industrial agriculture.

Seeing pixel cropping in the field invited questions and ideas for what else could be done: What if you planted the crops in hexagons or circles or Turing patterns instead of squares? And then what size should the pixels be? What happens if we grow thirty crops instead of six? Could we create a game or write an algorithm to design optimal crop neighborhoods? And match the location of certain crops to soil heterogeneities? Or what if you just threw all the seeds in the field and let the plants choose where to grow? How could we get rid of the walking lanes? What's the best way to attract parasitoid wasps or accommodate partridges? Would this work in other pedo-climatic and socio-technical contexts? Would the outcomes change over time, if we let the system self-regulate for several years? And so on. Coming back to the second framing question of this thesis, *how much crop diversity (how big a step) is needed?*, here I again conclude that the more diversity, the better—if your goal is to get people talking about alternative futures. This conclusion is also supported by the museum story in Chapter 7.

Brand (2008) and Darnhofer (2020) share a conceptual node in proposing that dynamic and long-term thinking are necessary for opening opportunities for change and for inspiring new ways of imagining and (re)making worlds. Long-term and process-relational thinking are both projects to "make other worlds possible" (Darnhofer 2020, p. 522). Consider again the Clock of the Long Now: the 10,000-year future is farther away than anything we can imagine, and the idea of building a clock that will last that long is a little nuts. But it is not about whether the clock will actually be built, and I argue that the same holds for pixel cropping or any other free-form, post-productivist, post-automation, response-able iteration that might succeed it when we learn to let go of our monoculture origins. It is about changing the way we imagine farming futures.

In the farming systems design research, the concepts of 'positive deviants' (Adelhart Toorop et al. 2020), 'bright spots' (Bennett et al. 2016), and 'lighthouse farms' (Valencia et al. 2022) valorize farmers and other food systems actors who are disrupting the *status quo* by already crafting future farming worlds. These out-there ideas and embodied examples serve as a collection of possible starting points for imagining a different future where farmers are not locked into a regime of homogeneity, for thinking differently about measures of success, and for activating and anticipating multiple temporal scales: an invitation to step aboard the ship *The Impossible* (Daumal 1959) and experience what for others is still only an imagination. Meanwhile, for those with a foothold in productivist conventions, the mono—strip—pixel transition framework facilitates thinking beyond the last step in the framework by providing an anchor in the past and present: "a place of integrity to which we can return from exploration, to begin new explorations" (Westley and Folke 2018, p. 5). The two steps, strip and pixel, are only two imaginations—with origins in monoculture—for how industrial farming could be rearranged towards higher-resolution agrobiodiversity and ecological relations, and they should be seen as such. In observing, analyzing, and critiquing them, we are invited to imagine something even further afield, something even more radical, something not yet possible (Wyborn et al. 2020).

8.5. Concluding remarks

In this thesis I have examined the prospects for leveraging in-field crop diversity as a solution for meeting the multifaceted demands placed on farmers by society. To do this I utilized concepts and methods drawn from agronomy, ecology, science and technology studies, and design. Pulling these threads together in this General Discussion, I have proposed that even more intricate and expansive braiding is needed if we are to arrive at a true societal shift away from monocultures and towards realizing diversified industrial cropping systems.

Coming back to the *Whole Earth Catalog's* notion of tools, we can think of strip cropping as one tool that we already have today: what can we achieve with it? This research suggests that many of (Dutch) society's current demands on agriculture can be met with strip cropping, all without breaking too far out of the familiar industrial farming box. Strip cropping is a tool for the present and near future, a current entry point. The research also indicates that while promising from an ecological perspective, pixel cropping cannot (yet) meet all of society's demands on farming, in part because the tools to make it work well do not exist yet, and perhaps because it adheres too closely to its monocultural-conceptual origins. Does that mean we should promote strip cropping as *the* solution and forget about pixel cropping, or any other frontier farming practice in the early stages of imagination? No—with my own critique of the pixel cropping logic in mind, I have argued that we need current entry points as much as we need un-proven, forward-looking (and perhaps a bit flawed) options on the table if we are to move effectively away from the problems of industrial monocultures and towards longer-term, process-relational, diversified industrial agroecosystems, i.e. transformative change.

Changing the way we imagine farming futures has big implications for agricultural systems research seeking to support agricultural transitions. In summary, I have suggested here that it implies rethinking not only *what* we research but also *how* we research it. Specifically, I posit that it will require making openings for:

- Agroecological research conducted at longer-term and larger spatial scales;
- Conceptions and assessments of success which account better for agroecological relations, a plurality of knowledge forms, emergent complexity at the system level, and dynamic learning;
- A reframing of heuristics devised to facilitate agricultural transitions and the field experiments designed to test them, to make room for disruptively innovative imaginations;
- Design processes that center farmers' embodied experiences, cultivate complexity, and facilitate more pluralistic and less-essentialized roles for technology.

Future research adopting these motivations in industrialized settings should test and assess a more diverse assemblage of diversification practices in a wider range of cropping systems, pedo-climactic regions, and socio-technical contexts. It should also seek to involve actors outside the standard bubble of agricultural academia in truly transdisciplinary approaches to iteratively imagine, design, test, and assess these practices. This would allow for expanding the impact of crop diversity research by broadening and deepening our understanding of what works, where, for whom, and in which future.

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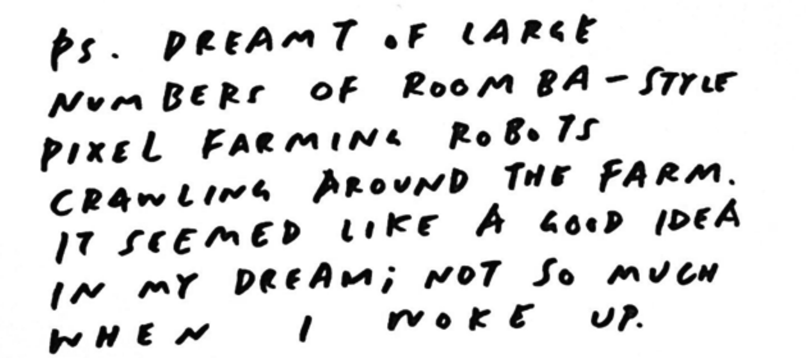

PS. DREAMT OF LARGE NUMBERS OF ROOMBA-STYLE PIXEL FARMING ROBOTS CRAWLING AROUND THE FARM. IT SEEMED LIKE A GOOD IDEA IN MY DREAM; NOT SO MUCH WHEN I WOKE UP.

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Summary

This thesis begins with the premise that the current industrial, monocultural model of crop production practiced widely in Europe is no longer tenable and that alternatives are urgently needed. Following decades of intensification, specialization, and mechanization in crop production, arable farming landscapes have become simplified—characterized by a narrow handful of crops grown in predominantly short rotations sustained by high (agrochemical) inputs. In the Netherlands, this trend is being linked to socio-ecological crises such as biodiversity loss and nitrogen pollution, and society is calling on farmers to rethink their practices in favor of producing not only food and feed, but also agroecosystem services (AES). Here, crop diversification comes into the story as a key lever with the potential for generating positive system change at both the Dutch and European levels. Several recent global meta-analyses examining the impacts of crop diversification on AES delivery have concluded that field- and landscape-scale crop diversification can indeed enhance AES delivery while maintaining expected yields, but it remains an open question whether these effects are generalizable to the industrial European context.

In this thesis I explore the prospects for industrial-scale diversified agriculture from agronomic, ecological, socio-technical, and design perspectives, in the European and Dutch contexts. Combining agronomic and ecological approaches with socio-technical discourse and design methodologies, the work contributes to a necessary new wave of systems-level research seeking to better understand the AES delivery potential of diversified cropping systems and their management implications, and thereby provide learnings to support policy makers in realizing the European Commission's sustainability goals. Following an accumulation of evidence in the literature that higher-resolution crop diversity delivers greater benefits, I work with a gradient of diversification options which progresses in complexity from monoculture to strip cropping to pixel cropping. These three steps are conceived of as both practical options for farmers and used as conceptual tools for imagining and discussing a possible transition pathway away from the current monocultural paradigm. Using literature review, field experimentation, novel heuristic frameworks, and interactive multi-stakeholder design projects, I assess each step by asking three framing questions:

- *Do these methods (steps) work?*
- *How much crop diversity (how big a step) is needed to achieve both production and ecological goals?*
- *And what does cultivating that much diversity mean for management and technology?*

Before presenting the research, I offer an ABCs of the thesis (Chapter 2). The ABCs is meant as a supplement to support readers approaching the research from outside their own discipline and give transparency to the multiple genres of disciplinary jargon used throughout the thesis. In the first research chapter (Chapter 3), we aimed to gain a delimited overview of the research to date on AES delivery from diversification practices: what has been studied, what has not. The review

focuses on the most practiced diversification method—introducing legumes into rotations—and asks what methods and performance indicators for legume inclusion are being studied by the agricultural research community in Europe. The key finding of the review is that despite indications that legumes can provide many services, current research focuses largely on a limited number of performance indicators which relate primarily to production-oriented AES. Linking this finding to historical trends and farmer surveys published in other studies, we conclude that this limited focus is both counter to the knowledge needs of farmers seeking to increase their legume adoption and likely the result of self-reinforcing socio-technical regimes which prioritize production over non- or indirectly-marketable AES. Drawing on these findings, we suggest that research on crop diversity practices and impacts should itself be diversified to include a wider range of species, practices, and AES indicators.

The findings of the review provided direction for the next chapter, which investigates the diversification method and AES we found to be least reported on in the literature: strip cropping and pest and disease control. Chapter 4 utilizes empirical data from two organic long-term crop diversification on-station experiments in the Netherlands where biocontrol potential was monitored in wheat (three years data) and disease control was monitored in potato (seven years data). To orient the analysis, we first introduce a heuristic framework for conceptualizing diversity as consisting of in-field practices that create heterogeneity in three dimensions: time, space, and genes. Together these dimensions are visualized as a three-dimensional space within which diversification practices can be positioned based on how they score in each dimension. The objective of this framework is to describe and visualize the ways that farming practices mobilize diversity, with an outlook on the potential to use the framework as a quantitative tool for linking in-field diversity to AES delivery responses. As a first step in this direction, in Chapter 4 we utilize the three-dimensional diversity heuristic as the conceptual basis for analyzing the field data. The key findings of this analysis are: strip cropping was highly effective for controlling potato late blight (*Phytophthora infestans*); strip cropping of multiple potato cultivars lowered disease spread rates compared to single cultivar strips; and wheat sown in strips supported a greater abundance and more diverse community of epigeic natural enemies than wheat monocultures, but species mixing within strips did not further increase biocontrol potential compared to sole-wheat strips. We conclude from these findings that increasing in-field diversity via strip cropping can indeed enhance AES delivery, but that diversifying in multiple dimensions within the strip may not always be necessary, depending on the service being targeted. Such a conclusion calls for more research into what might be the optimal level of diversity that allows farmers to meet sustainability goals while also balancing production demands and management complexity. In Chapter 5 we respond to this call.

In Chapter 5 we utilize three years of empirical data collected in another long-term organic crop diversification experiment in the Netherlands which tested a spectrum of diversification practices that spanned a continuum from less (strip cropping) to more (pixel cropping) complex. In cabbage—wheat and potato—grass crop pairs, we measured a range of AES indicators selected to capture both common agronomic measures of success and address research gaps identified in Chapter 3. To analyze the field data, we extend the functionality of the three-dimensional diversity heuristic presented in Chapter 4 by devising a system for calculating scores for each diversity dimension. This extension allows the heuristic to be used as quantitative tool for linking multi-dimensional in-field diversity to AES responses. Using the new method, we calculate diversity scores for each treatment tested in the field experiment and use these scores as predictor variables in the statistical analyses. Here we find that while the effects of specific treatments on performance indicators were difficult to generalize, increasing three-dimensional diversity overall had a positive effect on several indicators, namely associated biodiversity (weed species Shannon diversity) and natural enemy activity density. On the other hand, high-resolution diversity had a negative effect on several production indicators. In this analysis we observe a tipping point between the most diverse strip cropping treatment and the pixel cropping treatment, with pixel cropping performing notably poorly in terms of production. These findings suggest that there may be an inherent limit to the agroecological potential of diversification, highlighting a trade-off between ecological and production aims at resolutions of diversity higher than strip cropping. We hypothesize that this limit is likely imposed (at least in part) by a lack of appropriate technologies which could facilitate optimal management of complex cropping systems, and that reconciling management shortcomings in such systems could be a way to avoid the observed tipping point. To do so, however, new management tools will need to be developed.

In Chapter 6 we delve into to the question of untangling the technological challenge of designing the management tools needed to facilitate a conceptual and practical move towards more complex cropping systems in the future. We explore some of the options for how high-resolution crop diversification could be operationalized in practice by looking at who (or what) might do the work. Specifically, we look at the prospect of robotics and automation, and delve into the question of what appropriate automation for agrobiodiverse cropping systems might be, using pixel cropping as a case study and a proxy for a wider range of agroecological modes of farming. The research involved a series of discussion groups, workshops, design challenges, and interviews held in and around two pixel cropping trials in the Netherlands, in which we asked the participants to imagine what automation for highly diverse cropping systems might be, do, and look like. Through the designs proposed by workshop participants and through interviews with a farmer testing a field robot, we observed that expanding the notion of automation could make necessary room for both high- and lo-tech options to coexist and for collaborative modes of engagement to emerge. In our analysis we bring together these findings with historical trends and socio-technical discourse. Our key conclusion is that meeting the multifaceted conceptual and management demands of highly diverse cropping systems will likely require an equally multifaceted approach which takes a less essentialized position on automation and instead conceives of it as a dynamic range of context-dependent options and directions. Doing so will require both tool designers and users to expand their view of what automation could mean in different circumstances and allow for a plurality of solutions to emerge.

In Chapter 7 I reflect on the process of being involved in the exhibition *Countryside, the Future* which was installed at the Solomon R. Guggenheim Museum in New York from February 2020 to February 2021, and I present a visual narrative of the content I co-produced for the exhibition. The show explored the radical changes occurring in Earth's rural spaces, and one chapter examined the role of agriculture in driving these changes. For that chapter I collaborated with artists, designers, and researchers from a diversity of disciplinary backgrounds to produce a narrative about the competing agro-futures unfolding in the Netherlands. The narrative explores the role of technology in shaping food production, taking pixel cropping as the protagonist in a story where technological advances and ecological ambitions meet.

To conclude the thesis, I present a general discussion in which I reflect on the premise and prospects of the research as a whole (Chapter 8). I engage with the notion of a 'monoculture mindset' as a way to revisit the aims and questions posed in the General Introduction through new critical lenses, proposing that the mono—strip—pixel framework has great value in its capacity to demonstrate practical options and catalyze new thinking but is also inherently limited by its own framing. Through the field studies I showed that that both strip and pixel cropping have potential to meet various societal demands. Strip cropping in particular offers a good outlook for Dutch farmers seeking to enhance disease mitigation in organic potato production, as well as the potential to increase associated biodiversity and natural enemy populations, all without incurring yield penalties or requiring big changes in machinery or field management. Pixel cropping offers a good outlook for biodiversity measures, but comes with a trade-off in production under the current management regimen and is tremendously labor intensive. Reconciling this trade-off may involve developing new (automated) tools or new community—work arrangements, like those explored in Chapter 6. Alternatively (or additionally), it could involve engaging new ways of conceiving agrobiodiverse solutions which center ecological relations rather than monocultural tropes—countering the research trends highlighted in Chapter 3 and going beyond the efforts to take a different approach in Chapters 4 and 5. To do so would have big implications for agricultural systems research seeking to support more diverse agro-futures.

In conclusion, I suggest that moving effectively towards diversified industrial cropping systems implies rethinking not only *what* we research but also *how* we research it. Specifically, I posit that it will require making openings for:

- Agroecological research conducted at longer-term and larger spatial scales;
- Conceptions and assessments of success which account better for agroecological relations, a plurality of knowledge forms, emergent complexity at the system level, and dynamic learning;

- A reframing of heuristics devised to facilitate agricultural transitions and the field experiments designed to test them, to make room for disruptively innovative imaginations;

- Design processes that center farmers' embodied experiences, cultivate complexity, and facilitate more pluralistic and less-essentialized roles for technology.

Samenvatting

Dit proefschrift start met de stelling dat de huidige industriële landbouw met monoculturen zoals die op grote schaal wordt toegepast in Europa, niet langer houdbaar is en er met spoed alternatieven nodig zijn. Na tientallen jaren van intensivering, specialisering en mechanisering in akkerbouw zijn agrarische landschappen veel minder divers geworden. Het platteland wordt nu gekenmerkt door een beperkt aantal gewassen die in overwegend korte rotaties worden verbouwd, doorgaans afhankelijk van hoge concentraties landbouwchemicaliën. In Nederland wordt deze trend gelinkt aan sociaal-ecologische crisissen zoals verlies de biodiversiteitcrisis en stikstofcrisis. De samenleving vraagt van boeren om hun werkwijzen aan te passen zodat er naast voedsel ook meer agro-ecosysteemdiensten worden geleverd. Gewasdiversificatie kan een sleutelrol spelen door een positieve systeemverandering op zowel Nederlands als Europees niveau. Recent hebben verschillende meta-analyses de impact van gewasdiversifiëring op AES bestudeerd en is geconcludeerd dat veld- en landschapsschaalgrootte inderdaad een positieve impact kunnen hebben op AES met vergelijkbare opbrengsten. Het blijft echter een open vraag of deze effecten gegeneraliseerd kunnen worden naar de industriële Europese context.

In dit proefschrift onderzoek ik de vooruitzichten van een gediversifieerde landbouw op industrieel niveau vanuit agronomisch, ecologisch, sociaal-technisch en ontwerp perspectief, in de Nederlandse en Europese context. Door het combineren van een agronomische en ecologische aanpak met een sociaal-technische beredenering en aandacht voor ontwerp methodes, draagt dit werk bij aan golf van onderzoek op systeemniveau dat streeft om het potentieel van AES van gediversifieerde gewassystemen en de implicaties van het management beter te begrijpen en tegelijkertijd inzichten te delen die beleidsmakers kunnen steunen in hun realisatie van de duurzaamheidsdoelstellingen van de Europese Commissie. Na een opeenstapeling van bewijs in de literatuur dat meer diversificatie van gewassen meer voordelen geeft, werk ik met diverse diversificatieopties die verlopen in complexiteit van monocultuur, via strokenteelt naar pixelteelt. Deze drie stappen zijn bedacht om zowel praktische opties voor boeren te geven, alsook conceptuele hulpmiddelen voor de beeldvorming en discussie van een mogelijke transitie, weg van het huidige paradigma waarin monoculturen de standaard zijn. Door gebruik te maken van literatuur, veldexperimenten, nieuwe heuristische kaders en ontwerpprojecten met meerdere belanghebbenden, onderzoek ik elke stap aan de hand van drie kadervragen:

- *Werkt deze methode?*
- *Hoeveel diversificatie van gewassen (welke stapgrootte) is nodig om zowel productie- als ecologische doelen te behalen?*
- *Wat betekent zoveel diversificatie voor het management en technologie?*

Alvorens het onderzoek te presenteren, geef ik een overzicht van de relevante termen in dit proefschrift (hoofdstuk 2). Het overzicht is bedoeld als supplement om lezers die minder bekend zijn met dit onderzoeksgebied te helpen en om helderheid te geven over de verschillende genres van het vakjargon dat in deze proefschrift wordt gebruikt. In het eerste onderzoekshoofdstuk (hoofdstuk 3) kijken we naar het onderzoek wat tot dusverre gedaan was op het gebied van AES vanuit diversificatie oogpunt. Het overzicht focust zich op de meest voorkomende diversificatiemethode – het introduceren van peulvruchten in de rotaties – en bekijkt welke methodes en prestatie-indicatoren voor peulvruchteninclusie in het landbouwonderzoek worden onderzocht. De belangrijkste bevinding van deze review is dat hoewel er indicaties zijn dat peulvruchten verschillende diensten kunnen bieden, het huidige onderzoek vooral gefocust is op een beperkt aantal prestatie-indicatoren die zich vooral richten op productiegerelateerde AES. Door deze bevinding te koppelen aan historische trends en enquêtes onder boeren die in andere studies zijn gepubliceerd, concluderen we dat deze gelimiteerde focus tegen de kennisbehoeften van boeren is die hun peulvruchtenadoptie willen laten toenemen. Dit is waarschijnlijk het resultaat van de zelfversterkende sociaal-technische regimes die productie prioriteren boven niet of slechts indirect verkoopbare AES. Op basis van deze bevindingen stellen we voor dat onderzoek naar de praktijken en impact van de diversificatie van gewassen zelf diverser zou moeten zijn door een breder scala aan soorten, praktijken en AES-indicatoren op te nemen.

De bevindingen van dit overzicht gaven richting voor het volgende hoofdstuk, dat de verschillende diversificatie methodes en AES onderzoekt die het minst gerapporteerd zijn in de literatuur: strokenteelt en plaag- en ziektebestrijding. Hoofdstuk 4 gebruikt empirische data van twee biologische langetermijn diversificatie-experimenten in Nederland waar potentieel voor biocontrole in tarwe werd gevolgd (data van drie jaar) en waar ziektebestrijding in aardappels werd gemonitord (data van zeven jaar). Om richting te geven aan de analyse introduceren we eerst een heuristisch raamwerk om diversiteit te conceptualiseren bestaande uit praktijkoefeningen uit het veld die heterogeniteit creëren in drie dimensies: tijd, ruimte en genen. Samen worden deze dimensies gevisualiseerd als een driedimensionale ruimte waarin diversificatiepraktijken kunnen worden gepositioneerd gebaseerd op hoe ze scoren in elke dimensie. De doelstelling van dit raamwerk is om de manieren waarop landbouwpraktijken diversiteit mobiliseren te beschrijven en visualiseren, met het vooruitzicht op het potentieel om dit raamwerk te gebruiken als een kwantitatief hulpmiddel om diversiteit in het veld en AES leveringsresponses te linken. Als eerste stap in deze richting gebruiken we in hoofdstuk 4 de driedimensionale diversiteitsheuristiek als een conceptuele basis om de velddata te analyseren. De belangrijkste bevindingen zijn: strokenteelt was zeer effectief om fytoftora (*Phytophthora infestans*) onder controle te houden; strokenteelt met verschillende aardappelrassen verlaagde de ziekteverspreidingssnelheid vergeleken met stroken met slechts een ras; tarwe gezaaid in stroken liet een grotere hoeveelheid en meer diverse gemeenschap van epigeïsche natuurlijke vijanden zien dan tarwemonoculturen, maar het mengen van tarwesoorten in de stroken zelf, verhoogde het potentieel voor biocontrole niet verder in vergelijking met stroken met een enkele tarwesoort.

We concluderen uit deze bevindingen dat toenemende diversiteit in het veld via strokenteelt inderdaad de AES kan verbeteren, maar dat diversificatie in meerdere dimensies per strook niet altijd nodig is, afhankelijk van de dienst die ten doel wordt gesteld. Een dergelijke conclusie vraagt naar meer onderzoek naar wat het optimale niveau van diversificatie is waarin boeren duurzaamheidsdoelen halen en tegelijkertijd ook een balans vinden met productie-eisen en complexiteit van beheer. In hoofdstuk 5 beantwoorden we deze vraag.

In hoofdstuk 5 gebruiken we drie jaar aan empirische data verzameld van een biologisch langetermijn gewasdiversificatie-experiment in Nederland. Hier hebben we geëxperimenteerd met een spectrum van diversificatiepraktijken dat zich uitspande van minder (strokenteelt) naar meer (pixelteelt) complexiteit. In gewasparen met kool – tarwe en aardappel – gras maten we een range van geselecteerde AES-indicatoren om zowel de gewone agronomische maatstaven voor succes te vangen, alsook de onderzoekshiaten in de literatuur te adresseren. Om de velddata te analyseren hebben we de functionaliteit van de driedimensionale heuristiek zoals gepresenteerd in hoofdstuk 4 uitgebreid met een scoringssysteem voor elke diversiteitsdimensie. Deze uitbreiding zorgt ervoor dat de heuristiek als kwantitatieve tool gebruikt kan worden om de multidimensionale velddiversiteit te linken aan antwoorden met betrekking tot AES. Met deze nieuwe methode berekenen we verschillende diversiteitsscores voor elke behandeling getest in het veldexperiment en we gebruiken deze scores als voorspelvariabelen in de statistische analyse. Hier vinden we dat, hoewel de effecten van de specifieke behandelingen op de prestatie-indicatoren moeilijk te generaliseren waren, het toenemen van driedimensionale diversiteit in zijn algemeenheid een positief effect had op verschillende indicatoren, namelijk bijbehorende biodiversiteit (onkruidsoorten Shannon diversiteit) en de activiteitsdichtheid van natuurlijke vijanden. Aan de andere kant had een toenemende driedimensionale diversiteit negatief effect op verschillende productie-indicatoren. In deze analyse zien we een omslagpunt tussen het meest diverse strokenteeltexperiment en de pixelteeltbehandeling, waarbij pixelteelt in het bijzonder slecht scoort qua productie. Deze bevindingen suggereren dat er een inherente limiet aan het agro-ecologische potentieel van diversificatie zit, dat een compromis markeert tussen ecologische en productiedoelstellingen bij een hogere diversificatieresolutie dan pixelteelt. We veronderstellen dat deze limiet waarschijnlijk wordt opgelegd (of ten minste gedeeltelijk) door een tekort aan geschikte technologieën die een optimaal management van een complex gewassensysteem kunnen faciliteren en dat het wegnemen van deze tekortkomingen een manier kan zijn om dit omslagpunt te voorkomen. Om dit te doen moeten er nieuwe beheertechnieken ontwikkeld worden.

In hoofdstuk 6 bekijken we hoe we de technologische uitdagingen kunnen ondervangen, benodigd om de management tools te ontwerpen die nodig zijn om een conceptuele en praktische stap te zetten naar meer complexe gewassystemen in de toekomst. We vonden een aantal opties voor hoe hoge resolutie gewasdiversificatie geoperationaliseerd kunnen worden in de praktijk door te kijken naar wie (of wat) het werk kan doen. We kijken specifiek naar het vooruitzicht van robotica en automatisering en duiken in de vraag van wat geschikte automatisering voor agrobiodiverse akkerbouw kan zijn, door pixelteelt als case study te gebruiken en een proxy voor een breder scala aan agro-ecologische manieren van landbouw. Het onderzoek omvatte een serie van discussiegroepen, werkgroepen, ontwerpuitdagingen en interviews gehouden in en rondom twee pixelteeltexperimenten in Nederland, waar we de deelnemers vroegen om zich voor te stellen wat automatisering voor zeer diverse gewassystemen zou kunnen zijn, doen en hoe het er uit kan zien. Door de voorgestelde ontwerpen van de werkgroepdeelnemers en door de interviews met de boer die een veldrobot testte, observeerden we dat uitbreiding van het begrip automatisering de benodigde ruimte kan maken voor het naast elkaar bestaan van high- als low-tech opties en om samenwerkingsvormen van betrokkenheid te laten ontstaan. In onze analyse brengen we deze bevindingen samen met historische trends en het sociaal-technologische discours. Onze belangrijkste conclusie is dat om te voldoen aan de veelzijdige conceptuele en managementeisen van zeer diverse teeltsystemen er waarschijnlijk een even veelzijdige benadering vereist is die een minder essentiële positie inneemt over automatisering en in plaats daarvan dit opvat als een dynamisch bereik van contextafhankelijke opties en richtingen. Dit vereist dat zowel de ontwerpers van landbouwmachines als de gebruikers hun blik moeten wijzigen met betrekking tot wat automatisering kan betekenen in verschillende omstandigheden. Dit kan een veelvoud van oplossingen naar voren laten komen.

In hoofdstuk 7 reflecteer ik op het proces van de betrokkenheid bij de expositie *Countryside, the Future* dat in het Solomon R. Guggenheim Museum in New York geïnstalleerd was van februari 2020 tot februari 2021 en presenteer ik een visueel verhaal van de content waaraan ik meegewerkt heb voor de expositie. De show gaf een weergave van de radicale verandering van de landelijke gebieden op aarde en een deel onderzocht de rol van landbouw bij het aansturen van deze veranderingen. Voor dat deel heb ik samengewerkt met kunstenaars, ontwerpers en onderzoekers uit diverse disciplinaire achtergronden om een verhaal te vertellen over de concurrerende landbouwtoekomsten die zich ontvouwen in Nederland. Het verhaal ontdekt de rol van technologie in het vormgeven van voedselproductie door pixelteelt als hoofdrolspeler te nemen in een verhaal waar technologische vooruitgang en ecologische ambities elkaar ontmoeten.

Ik rond dit proefschrift af door een algemene discussie te presenteren waarin ik reflecteer op het uitgangspunt en vooruitzicht van het onderzoek in zijn geheel (hoofdstuk 8). Ik sluit me aan bij het idee van een 'monocultuur mindset' als een manier om de doelen en vragen die in de algemene introductie zijn gesteld, door een nieuwe kritische lens te bekijken. Ik stel voor dat het mono – stroken – pixel raamwerk zeer veel waarde heeft in de capaciteit om praktische opties te demonstreren en om nieuw denken te stimuleren, maar tegelijkertijd ook gelimiteerd wordt door zijn eigen framing. Door de diverse veldstudies heb ik laten zien dat zowel stroken- als pixelteelt potentie hebben om aan verschillende maatschappelijke eisen te voldoen. Strokenteelt in het bijzonder biedt een goed vooruitzicht aan Nederlandse boeren die op zoek zijn naar het verbeteren van ziektebestrijding in biologische aardappelteelt, alsook de potentie om geassocieerde biodiversiteit en populaties natuurlijke vijanden toe te laten nemen. Dit alles kan zonder productieverlies of grote aanpassingen aan materieel of veldmanagement. Pixelteelt biedt een goed vooruitzicht voor biodiversiteit, maar dat heeft zijn weerslag op de productie en blijkt zeer arbeidsintensief te zijn met de huidige staat van techniek en management. Afzwakken van deze nadelen kan betekenen dat nieuw (geautomatiseerde) materieel of nieuwe gemeenschapssamenwerkingen worden ontwikkeld, zoals besproken in hoofdstuk 6. Als alternatief (of als aanvulling), kunnen nieuwe manieren van verstandhoudingen van agrobiodiverse oplossingen - die ecologische relaties als prioriteit geven boven monoculturele stijlfiguren - de strijd aanbinden. Daarmee kan het de onderzoektrends als besproken in hoofdstuk 3 keren en verder gaan dan de inspanningen om een andere aanpak te kiezen zoals in hoofdstuk 4 en 5. Dit zou grote implicaties hebben voor onderzoek naar landbouwsystemen dat gericht is op het ondersteunen van meer diverse agrotoekomsten.

Tot slot stel ik voor dat een effectieve transitie in de richting van meer gediversifieerde industriële landbouwsystemen impliceert dat we niet alleen heroverwegen wat we onderzoeken, maar ook hoe we het onderzoeken. Specifiek stel ik dat het nodig is om openingen te maken voor:

- Agro-ecologisch onderzoek uitgevoerd op langere termijn en grotere ruimtelijke schaal;
- Concepties en beoordelingen van succes die beter rekening houden met agro-ecologische relaties, een veelvoud aan kennisvormen, opkomende complexiteit op systeemniveau en dynamisch leren;
- Een herformulering van heuristieken die zijn ontworpen om landbouwtransities te vergemakkelijken en de veldexperimenten die zijn ontworpen om ze te testen, om ruimte te maken voor werkelijk innovatieve verbeeldingskracht;
- Ontwerpen van processen die de ervaringen van boeren centraal stellen, complexiteit cultiveren en meer pluralistische en minder essentiële rollen voor technologie faciliteren.

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About the author

Lenora Louise Evens Ditzler was born in San Francisco, California during the El Niño winter of 1982. She spent summers on a small island off the coast of Maine, where she learned to garden and eventually to cook the things she grew. During her senior year of high school, Lenora took a course about agriculture that involved driving around California in a bus for six weeks, camping and talking to farmers all day. At 17, she got her first paying job as a deck hand on a commercial lobster boat. She graduated high school with a passing grade in calculus, made possible by the generosity of a visionary math teacher who allowed her to submit a painting in place of taking the final exam. Lenora attended Bowdoin College, keeping her lobstering job on the side and graduating in 2005 with a dual bachelor's degree in environmental studies and visual arts. After college she continued to work in commercial fishing on boats in Maine, Washington, and Alaska, attending art residencies and occasionally cooking in restaurants in the off season. In 2010, she took a job as the Environmental Science teacher at the Oxbow School in Napa, California. There, she developed an honors-level garden-based science curriculum for art students which involved the construction of extensive organic vegetable gardens, a poultry operation, greenhouse, and apiary.

In 2014, Lenora left Oxbow to begin her academic career in the Agroecology MSc program at the Norwegian University of Life Sciences in Ås, Norway. During her studies, she visited Wageningen University on an Erasmus exchange semester. While there she took courses with the Farming Systems Ecology group (FSE) and became enamored with FarmDESIGN and the DEED research methodology. For her MSc thesis, she researched manure management on smallholder organic basmati rice farms in Uttarakhand, India. After graduating with her MSc, Lenora continued working on the basmati project in the Sustainable Agroecosystems Group at ETH Zürich. From there she was invited back to Wageningen to join FSE in 2017 as a junior researcher in the ESAP and Global One Health projects, during which she published work on affordances of systems analysis tools and whole-farm modelling. After a year in FSE Lenora was recruited to do a PhD in the DiverIMPACTS and LegValue projects, to which she brought her passion for conceptual models and visual thinking to empirical work with complex agroecosystems. Post-PhD, Lenora intends to continue carving out her own space at the interface between science and art.

List of publications

Peer reviewed scientific articles

Juventia SD, Selin Norén ILM, van Apeldoorn DF, **Ditzler L**, Rossing WAH (2022) Spatio-temporal design of strip cropping systems. *Agricultural Systems* 201:103455. doi:https://doi.org/10.1016/j.agsy.2022.103455

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Ditzler L, van Apeldoorn DF, Schulte RPO, Tittonell P, Rossing WAH (2021) Redefining the field to mobilize three-dimensional diversity and ecosystem services on the arable farm. *European Journal of Agronomy* 122:126197. doi: https://doi.org/10.1016/j.eja.2020.126197

Estrada-Carmona N, Raneri JE, Alvarez S, Timler C, Chatterjee SA, **Ditzler L**, Kennedy G, Remans R, Brouwer I, den Berg KB-v, Talsma EF, Groot JCJ (2020) A model-based exploration of farm-household livelihood and nutrition indicators to guide nutrition-sensitive agriculture interventions. *Food Security* 12 (1):59-81. doi: https://doi.org/10.1007/s12571-019-00985-0

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Ditzler L, Klerkx L, Chan-Dentoni J, Posthumus H, Krupnik TJ, Ridaura SL, Andersson JA, Baudron F, Groot JCJ (2018) Affordances of agricultural systems analysis tools: A review and framework to enhance tool design and implementation. *Agricultural Systems* 164:20-30. doi: https://doi.org/10.1016/j.agsy.2018.03.006

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Other publications

Ditzler L (2020) Pixel Farming. In: AMO, Koolhaas R (eds) Countryside, A Report. Guggenheim / Taschen, Köln

Ditzler L (2020) Planting Robots. *topos - The International Review of Landscape Architecture and Urban Design*, Green Technologies edn. Georg Media, Munich

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Agro-ecosystem services and drivers of variability in their delivery from legume crops and legume-based cropping systems

Writing of project proposal (4.5 ECTS)

- Redefining the field: mobilizing the benefits of crop diversity to enhance agroecosystem services delivery and resilience in temperate arable systems

Post-graduate courses (7.2 ECTS)

- Resilience of living systems; PE&RC (2018)
- Bugs at your service; PE&RC (2019)
- Basic statistics; PE&RC (2018)
- Generalized linear models; PE&RC (2019)
- Mixed linear models; PE&RC (2019)
- Multivariate analysis; PE&RC (2021)

Invited review of (unpublished) journal manuscript (1 ECTS)

- Agricultural systems: designing with farmers or for farmers? Examining the use of two design approaches to address complex agricultural challenges (2021)

Competence strengthening / skills courses (0.8 ECTS)

- Research data management; PE&RC (2018)
- Introduction to LaTex; PE&RC (2020)
- Strength of visual thinking; PE&RC (2020)
- Reviewing a scientific manuscript; WGS (2020)
- How to create impactful infographics and data visuals; YoungWUR (2020)
- Leading online meetings: how to make them fun, effective and purposeful; YoungWUR (2021)

Scientific integrity / ethics in science activity (0.6 ECTS)

- Scientific integrity and ethics; PE&RC (2018)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.9 ECTS)

- PE&RC First years weekend (2018)
- PE&RC PhD workshop carousel (2019)
- PE&RC Day (2019)
- Breeding for diversity symposium (2019)
- PE&RC Afternoon meeting; online (2020)

Discussion groups / local seminars or scientific meetings (9.3 ECTS)

- Resilience symposium; Klarenbeek, the Netherlands (2018)
- Women in science discussion group; Wageningen, the Netherlands (2018)
- DiverIMPACTS annual meetings; Lelystad, the Netherlands; Malmo, Sweden; several times online; Namur, Belgium (2018, 2019, 2020, 2021, 2022)
- LegValue annual meetings; Paris, France; several times online (2018, 2020, 2021)
- R Users discussion group; Wageningen, the Netherlands (2019)
- Agro-food robotics day; Wageningen, the Netherlands (2019)
- FIRA International forum for agricultural robotics; online (2020)

International symposia, workshops and conferences (6.95 ECTS)

- SDG conference toward zero hunger; workshop facilitation; Wageningen, the Netherlands (2018)
- 6th Farming systems design conference; oral presentations; Montevideo, Uruguay (2019)
- European conference on crop diversification; oral presentation; Budapest, Hungary (2019)
- LegValue virtual conference; oral presentation; online (2021)

Societally relevant exposure

- *Countryside, the Future* exhibition; Guggenheim Museum, New York (2019-2020)
- California studies, Urban School of San Francisco (2020, 2021, 2022)
- Countryside, the Future UN75 dialogue; online (2020)
- Design Academy Eindhoven studio design course (2020)
- "Pixel farming" in Countryside, a Report; Guggenheim/Taschen (2020)
- "Planting robots" in *topos*—International Review of Landscape Architecture and Urban Design (2020)
- Sustainability in agricultural chains; TUe & Design Academy Eindhoven, online (2021)
- Urbanism and the countryside: agriculture; ETH Zürich Department of Architecture (2022)

Lecturing / supervision of practicals / tutorials (9.7 ECTS)

- Analysis and design of organic farming systems (2018)
- Crop diversity experiments thesis ring (2018-2020)
- Integrated pest management (2019)
- Making an impact (2020, 2021, 2022)
- Emotions capita selecta (2020, 2021, 2022)
- Advances in intercropping (2021)

BSc/MSc thesis supervision (9.8 ECTS)

- Modelling pixel cropping
- Implementing strip cropping
- Productivity and quality of cabbage in pixel farming systems
- Productivity and quality of cereals grown in strip cropping systems
- Abundance and diversity of natural enemies in strip crops compared to monocultures
- Modelling strip and pixel cropping with FSPM

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